PV is conserved is our strongest statement to explain weather

But then where does PV come from?

ATM 405/561

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Outline

- Brief review of conservation of PV concept
  - https://www.notion.so/miamimapes/Horizontal-vorticity-and-PV-as-explanations-for-cyclones-anticyclones-2e6d2c075dba44699dc822ca5748e2e8

- Motivated by that, examine diabatic heating profiles with hungry eyes, and explain what you find. Practice telling an illustrated narrative well.

Questions about it

- 1. Using the concepts from the handout, and earlier homework, explain how patches or elements of **relative vorticity** advect other patches of **relative vorticity**, under the assumption that **relative vorticity** is sorta almost conserved.
- 2. Using the concepts from the handout, and earlier homework, explain how **planetary vorticity** is converted to **relative vorticity,** so that their sum, the **absolute vorticity,** is almost conserved. Consider a loop of air moving in latitude, and explain how the different Coriolis force felt by its northern and southern side act as a torque on the fluid loop.
- 3. Using the concepts from the handout, and the reading, explain how **static stability** is converted to **absolute vorticity,** so that **potential vorticity,** their **product,** which is the essence of vortices (cyclones and anticyclones) is really really almost conserved.
- 4. Using the concepts from the handout, strategize what you will look for in vertically resolved data about diabatic heating rate in the atmosphere to explain the ultimate source of PV.

Remember absolute vorticity?

- Absolute vorticity $\zeta_a = f + \zeta_{rel}$
- Exists from f alone, but the f part can also be *converted* to actual wind circulation ζ_{rel} whenever *air moves toward the equator*
- It is *amplified exponentially by convergence, and relaxed exponentially toward 0 by divergence:*
- $$\frac{D\zeta_{abs}}{Dt} = -\zeta_{abs}(\vec{\nabla}_p \cdot \vec{V})$$

Horizontal convergence also spreads material surfaces apart vertically

$$(\nabla \cdot \vec{V}) = -\frac{1}{\zeta_{abs}} \frac{D\zeta_{abs}}{Dt} = \frac{1}{A}\frac{DA}{Dt} = -\frac{1}{(\Delta p)}\frac{D\Delta p}{Dt}$$

So the RATIO **PV = -g ζ_a (∂θ/∂p)** remains unchanged by horizontal divergence!

$$\boxed{\frac{D}{Dt}(PV) = 0} - g\zeta_{abs}\frac{\partial \dot{\theta}_{diab}}{\partial p}$$

PV is conserved -- almost

Here is the key term that generates PV on the Earth

$$\frac{D}{Dt}(PV) = 0 \boxed{- g\zeta_{abs}\frac{\partial \dot{\theta}_{diab}}{\partial p}}$$

In this lab, you will learn (and show me you learned) about the nature of diabatic heating in the atmosphere.

PV is conserved -- almost

Here is the key term that generates PV on the Earth

$$\frac{D}{Dt}(PV) = 0 \boxed{- g\zeta_{abs}\frac{\partial\dot{\theta}_{diab}}{\partial p}}$$

1. We have available T tendencies, not theta tendencies, but can still eyeball the sense of the term above since $\dot{\theta}_{diab} = \dot{T}_{diab} \times \theta / T$
2. For large scale motions, f is most of the absolute vorticity. Therefore, you will estimate/explain:

PV is conserved -- almost

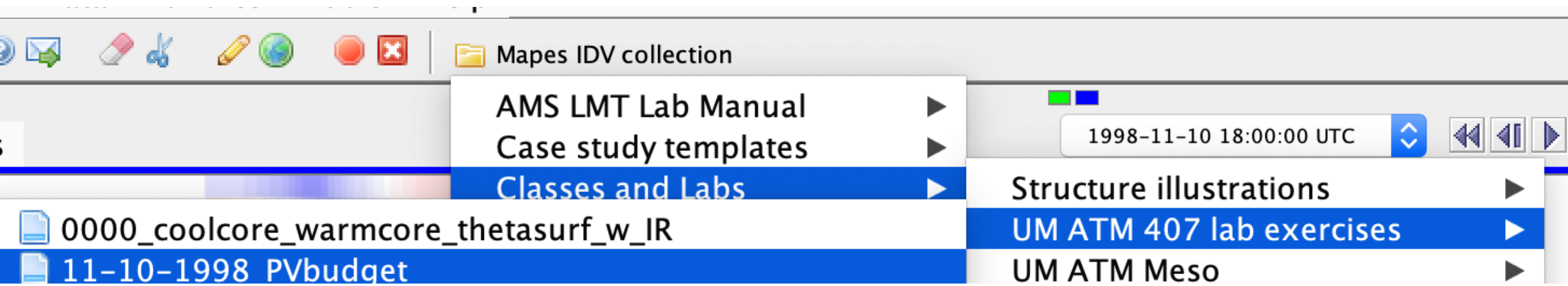
APPROXIMATE term that generates PV on the Earth

$$\frac{D}{Dt}(PV) = 0 \boxed{- gf\frac{\partial \dot{T}_{diab}}{\partial p}}$$

Mostly, you are looking for WHERE HEATING RATE INCREASES WITH HEIGHT, WEIGHTED BY f. In both hemispheres... so be careful with ”cyclonic”.

Assignment part 1: global view

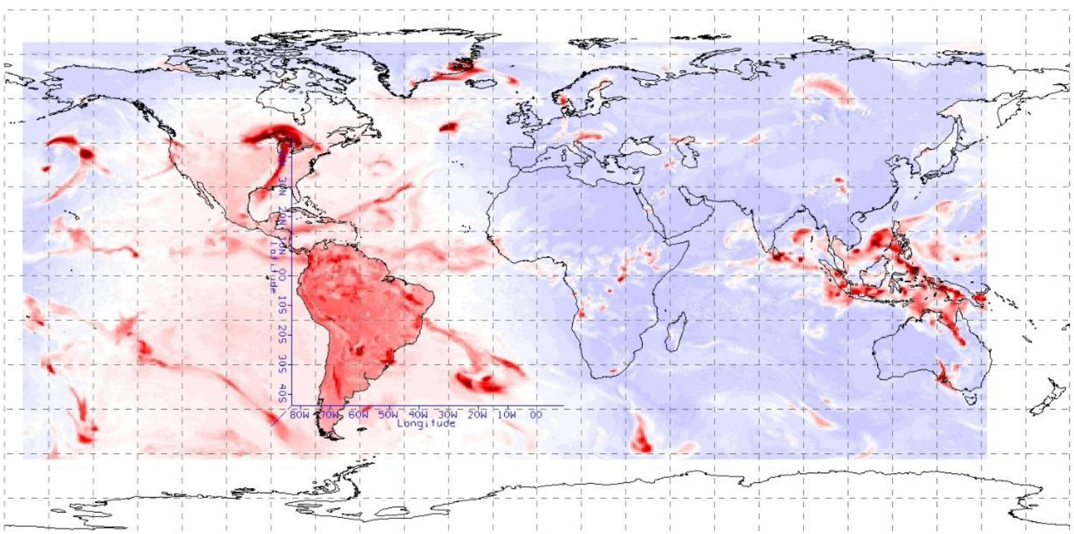
- Open the bundle 11-10-98 PV budget

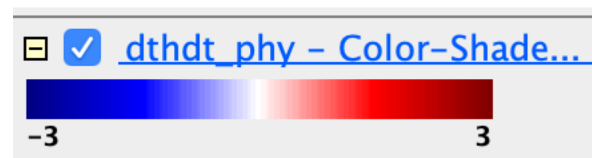


- Orient yourself to its displays, in **both windows**
  - a **pole-to-pole transect** of the **zonal mean** heating rates (averaged around the whole Earth)
  - A map view with many displays.

Assignment part 1: global view

1. What time of year is it? How can you see that fact in the all-physics (diabatic) column-integrated heating rate map dthdt_phy?



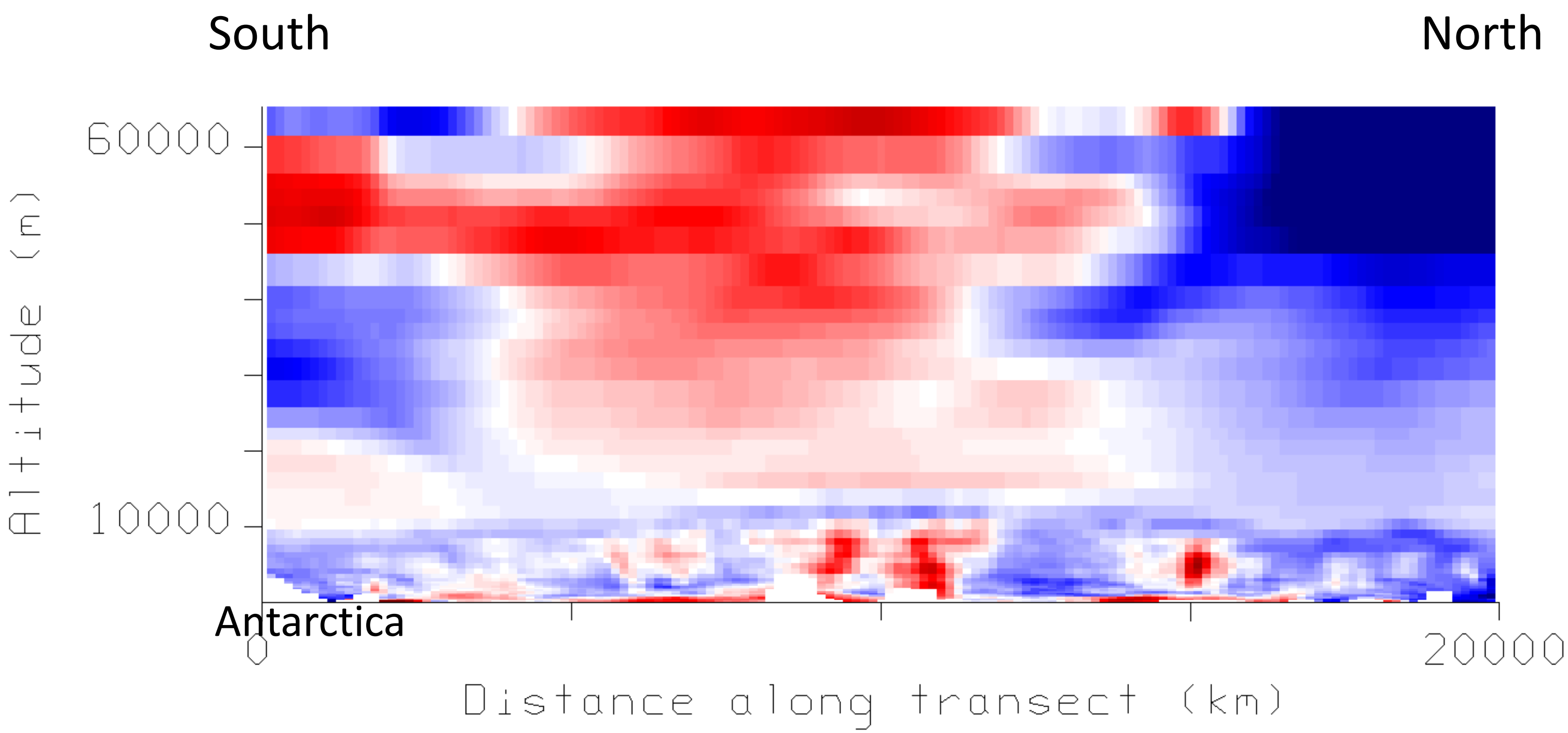


Assignment part 1: global view

- Now turn to the Transect View window, showing average cross sections all around the Earth. Create a slide showing the transect of diabatic heating. Label it: where is the south pole, the north pole? Hint: Antarctica is mountainous. The units of all heating rates are are K/s. What is the color range in K/day?

Assignment part 1: global view

Diabatic heating



Assignment part 1: global view

- Create slides with transect images showing each of these terms of the zonal mean heat budget.
- Use that imagery to explain the nature of all the main features in your total diabatic heating slide.

- These equations relate the terms displayed there:

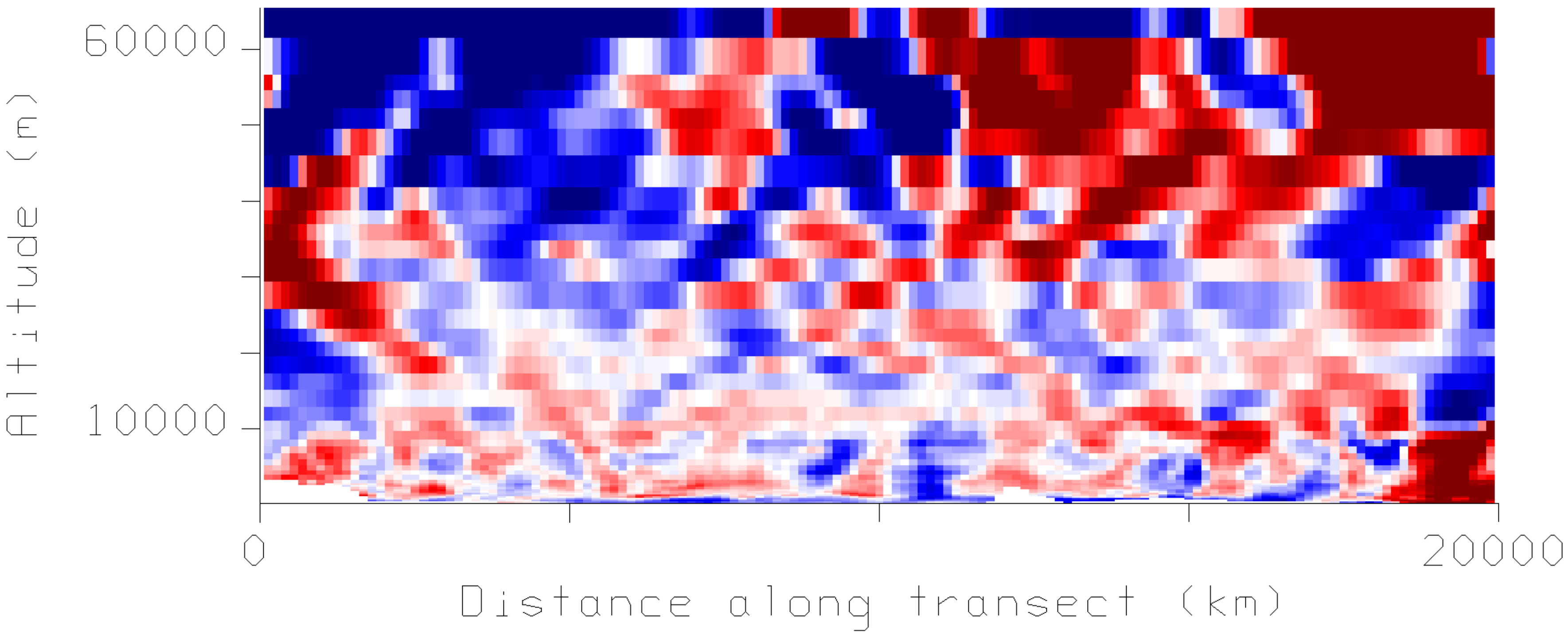
  $\partial T / \partial t$ = dynamical + diabatic + analysis

  diabatic = moist + radiative + turbulence

  radiative = longwave + solar

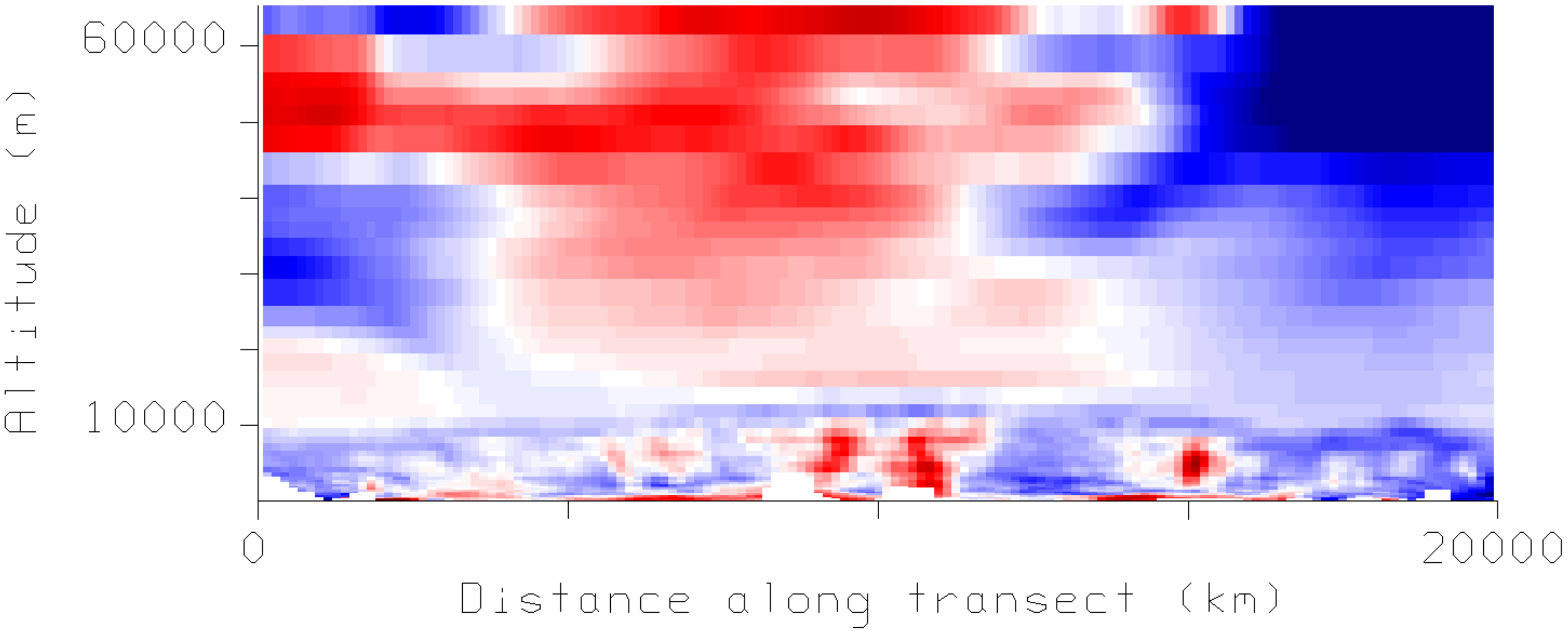
Assignment part 1: global view

- Dynamical heating



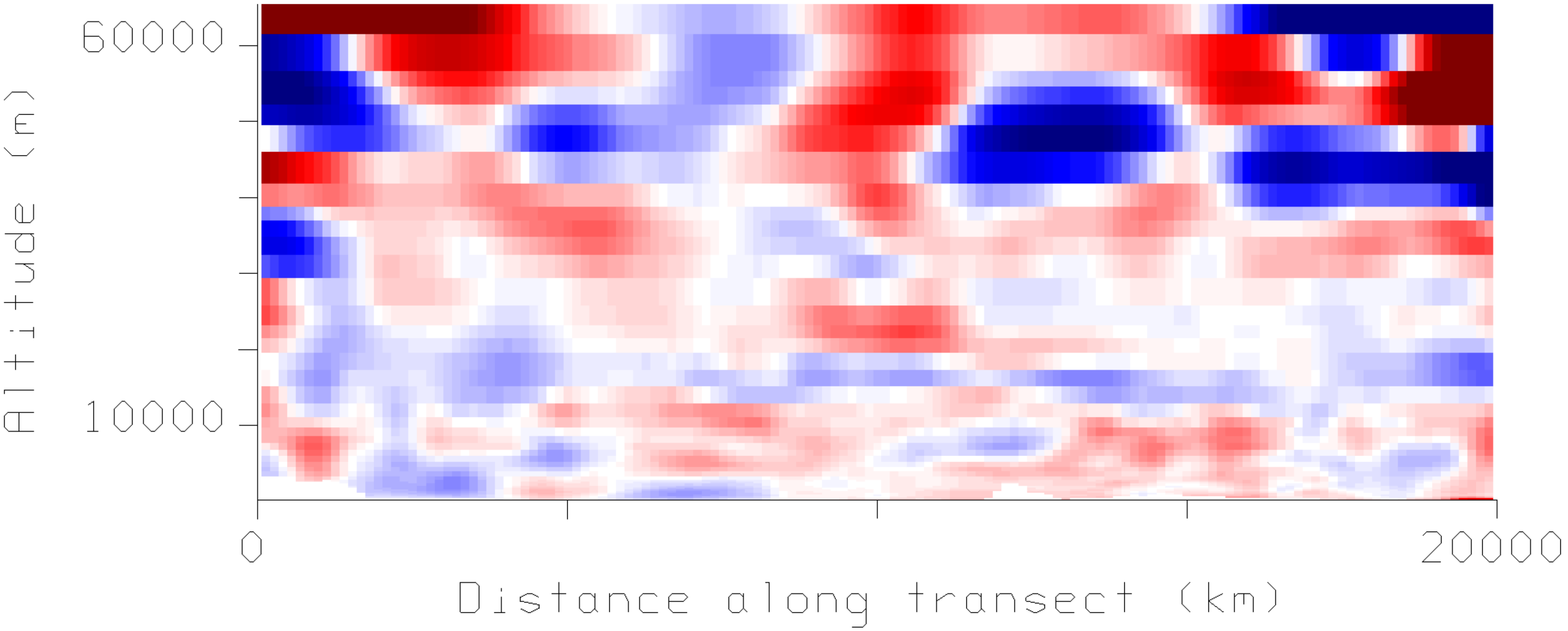
Assignment part 1: global view

- Diabatic heating



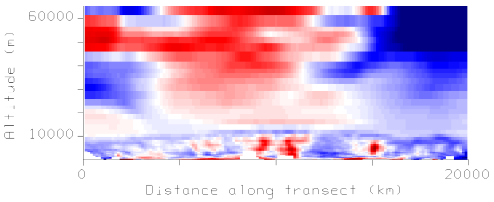
Assignment part 1: global view

- Analysis/Model errors

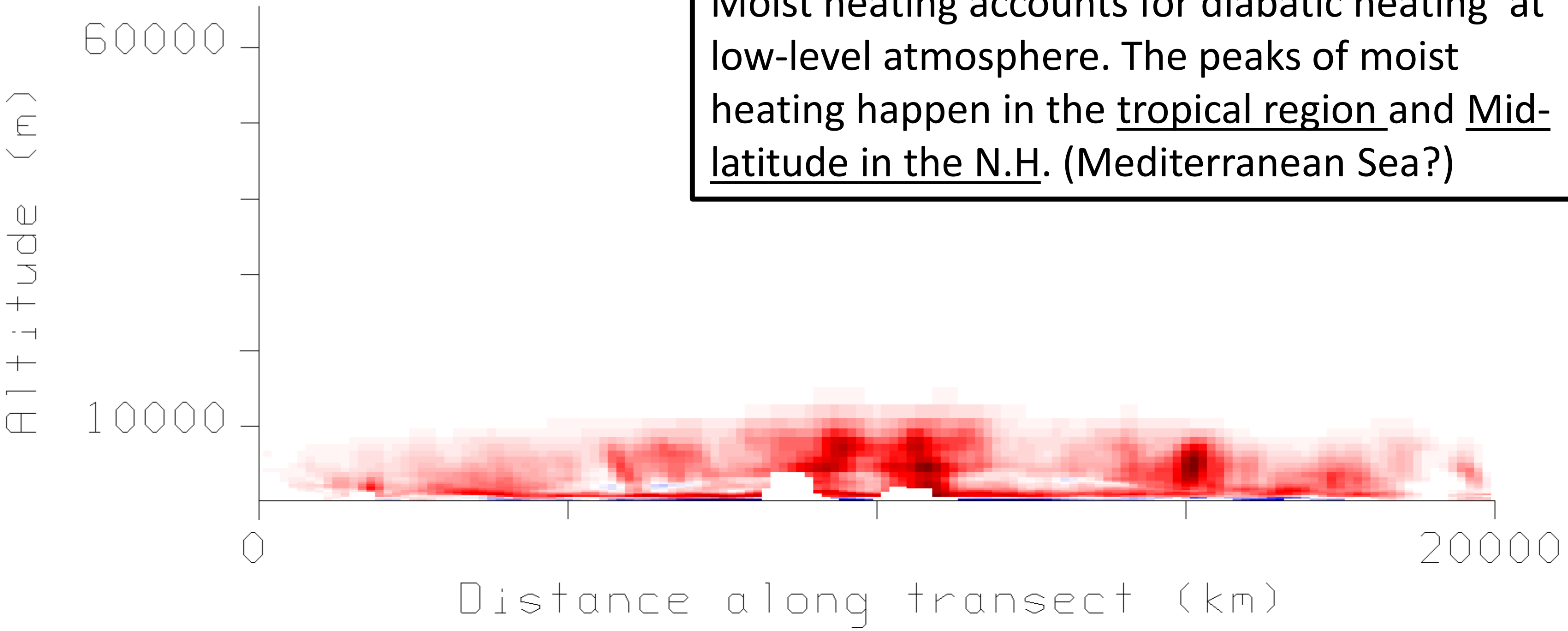


Assignment part 1: global view

- Moist heating

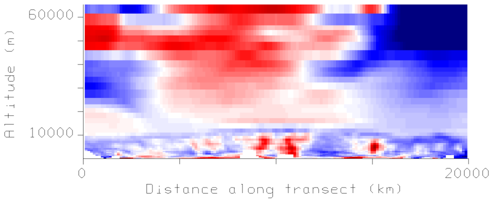


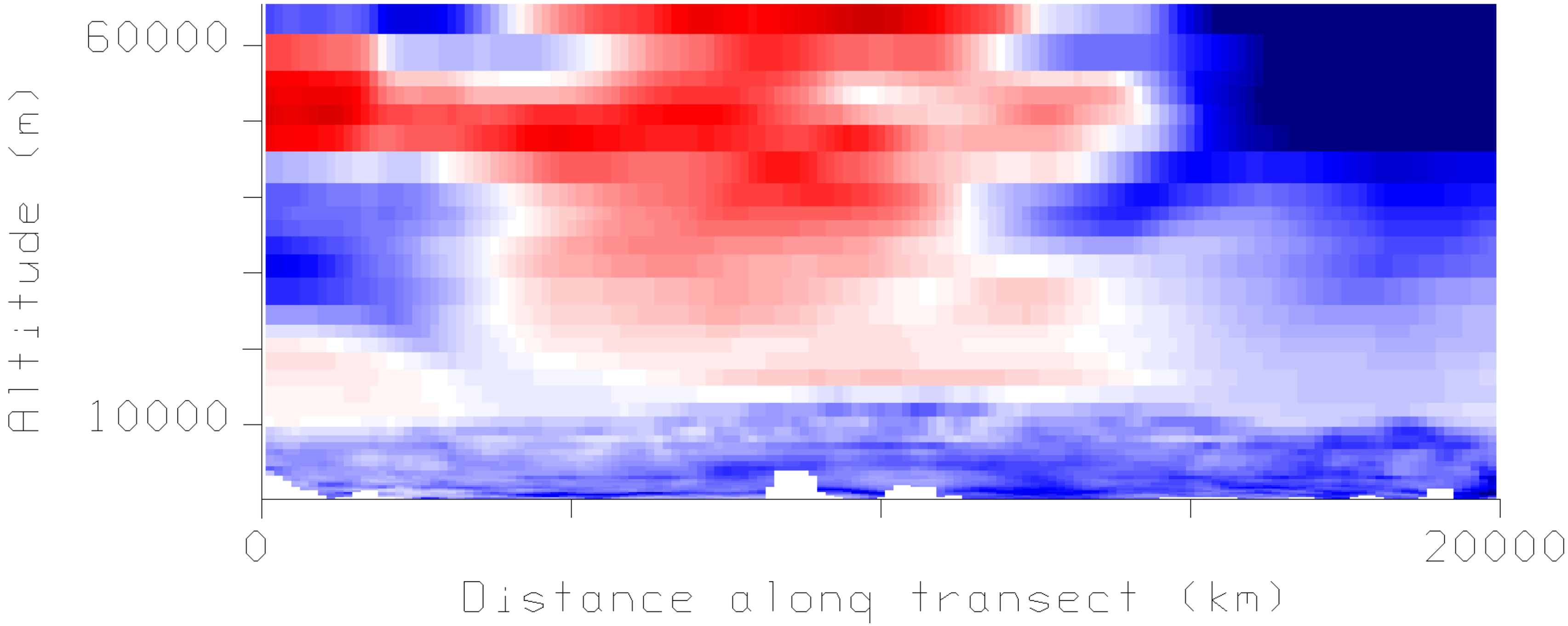
Moist heating accounts for diabatic heating at low-level atmosphere. The peaks of moist heating happen in the tropical region and Mid-latitude in the N.H. (Mediterranean Sea?)



Assignment part 1: global view

- Radiative heating

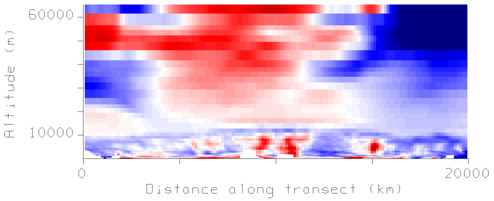


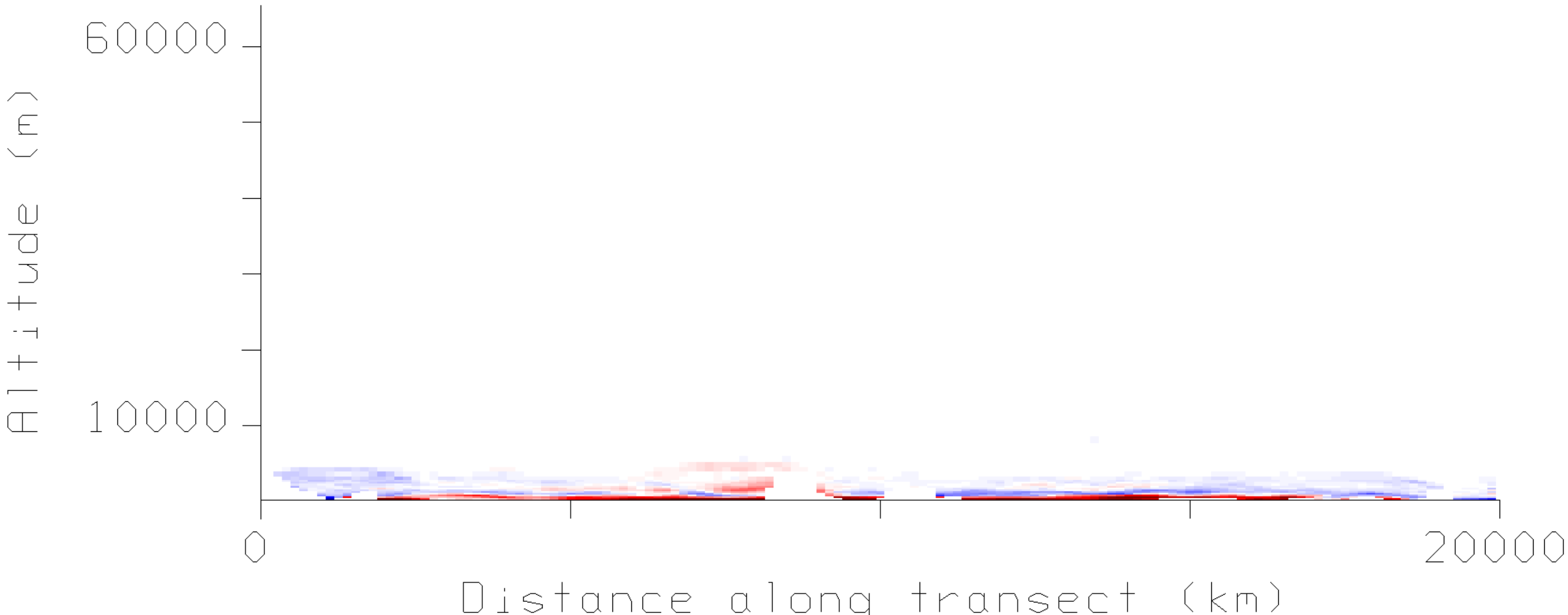


Radiative heating is the greatest part of diabatic heating happening at (10km - 60km).

Assignment part 1: global view

- Turbulence heating

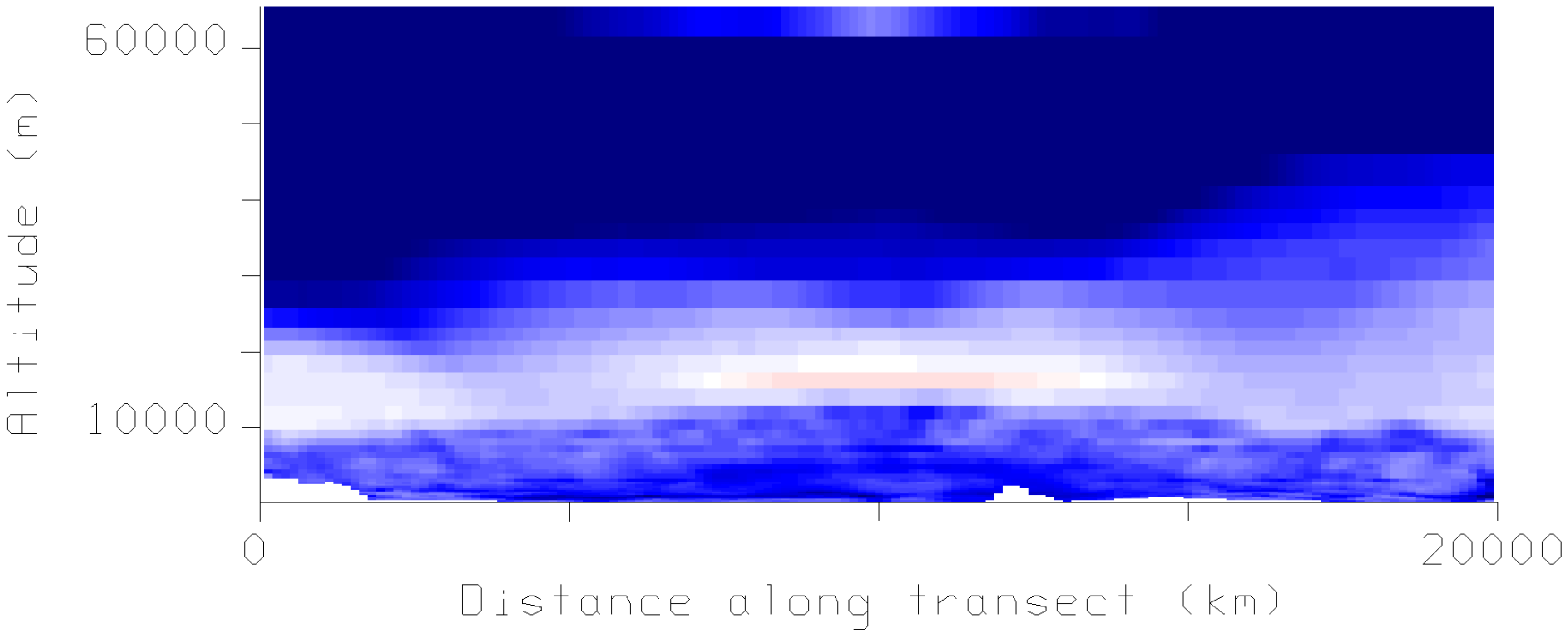




Turbulence heating is the smallest part of diabatic heating happening at low-level atmosphere.

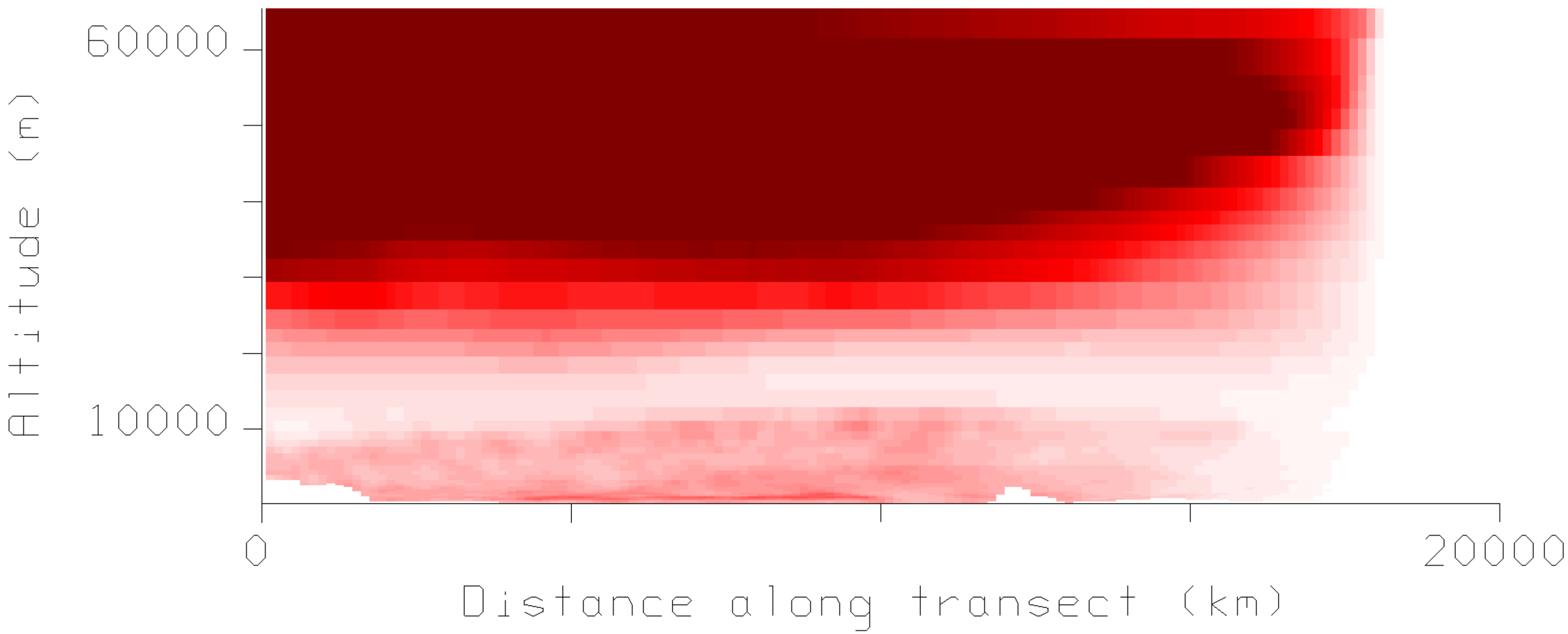
Assignment part 1: global view

- Longwave heating



Assignment part 1: global view

- Shortwave heating

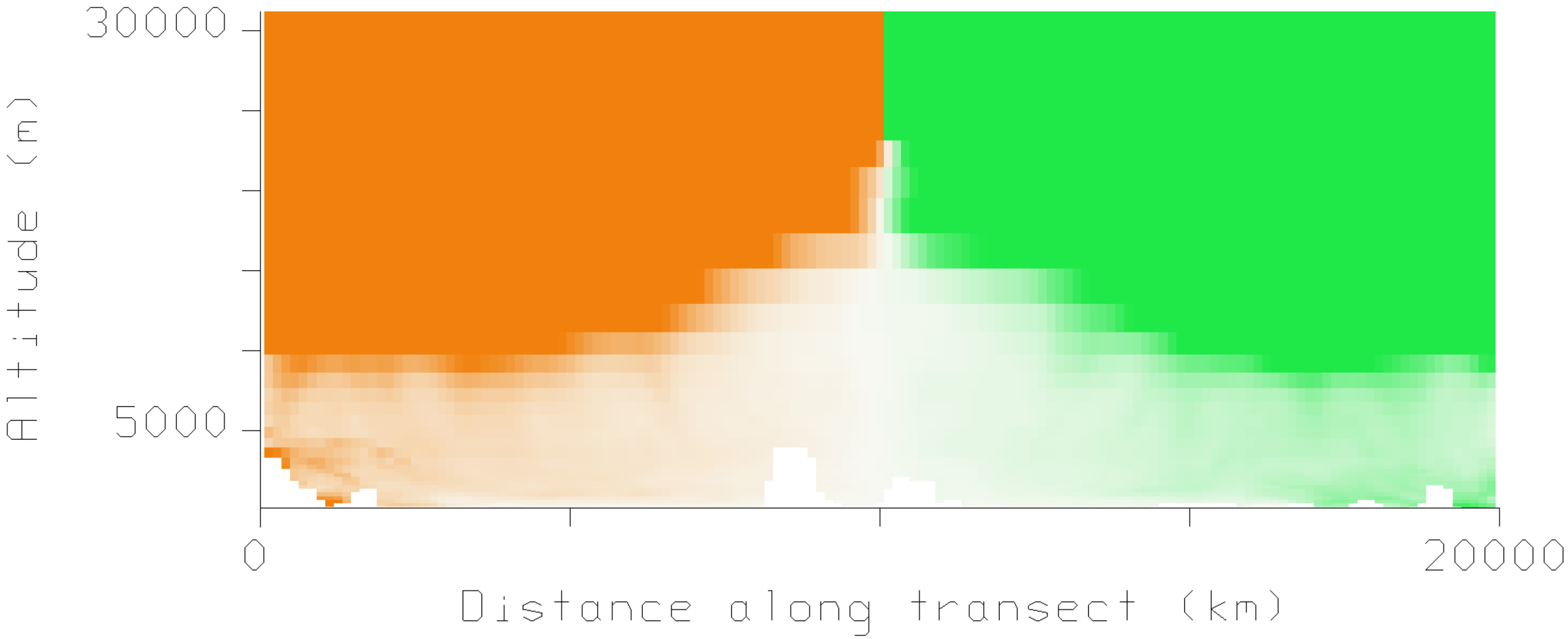


Assignment part 1: global view

- From your total diabatic heating, indicate areas where PV tendency is positive and negative. Also label these areas as cyclonic or anticyclonic tendencies.
- Does the *PV transect itself* resemble areas where your PV *tendency* is strong?
- Is PV mostly contained in the vorticity factor of its product, or the static stability factor? Show and label images to explain your answer.

Assignment part 1: global view

- PV



Assignment part 2: Local view

- Now activate the *cross section displays in the map view window.*
- These are like the cross sections you have examined before: you can drag them around to storms or other features
- Drag them to north-south positions that slice through tropical and higher latitude weather features that interest you (as seen on the other displays).

Legend explanation for cross sections

$\partial T / \partial t$ = dtdt_tot (physics) + dtdt_dyn (advection) + dtdy_ana

(ana is *analysis*; a "missing" tendency needed to make the observed $\frac{\partial T}{\partial t}$; reflecting the sum of all model errors)

diabatic tot = moist (mst) + radiative (rad) + turbulence (trb)

rad = lwr + swr

longwave

shortwave

analysis (0 for perfect model)

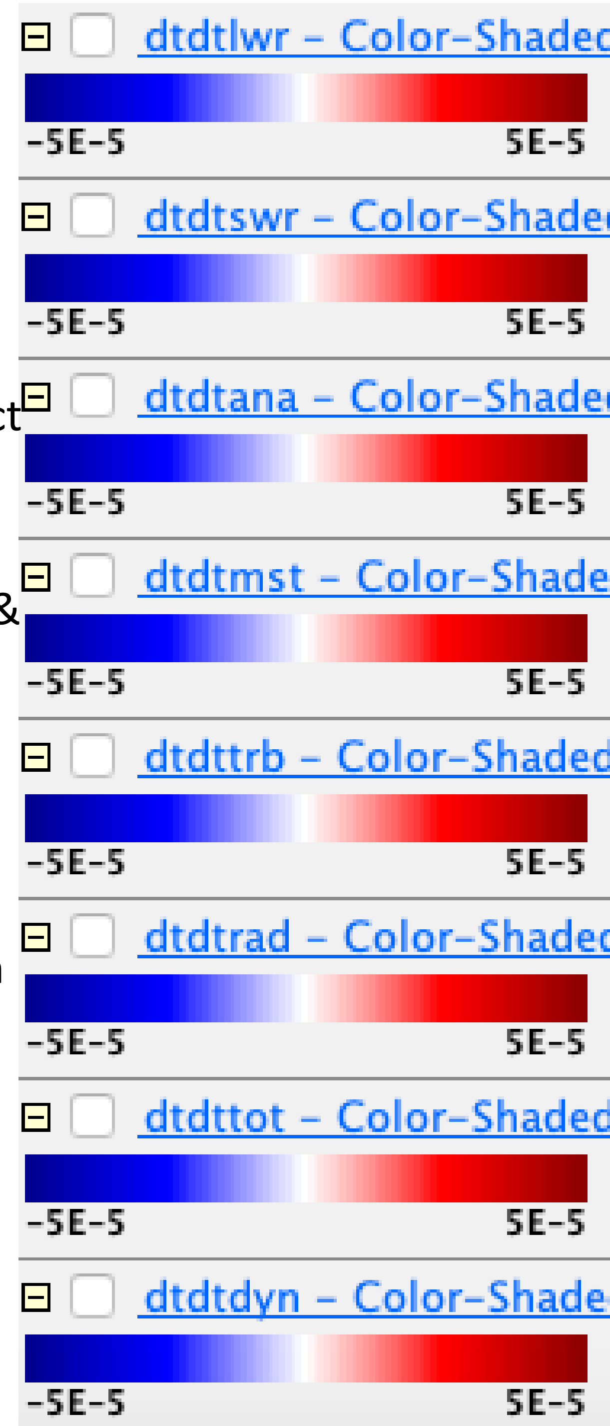
moist mst (convection & cloud cond.)

turbulence (PBL)

SW+LW radiation

total physics ("diabatic")

dynamic (advective)



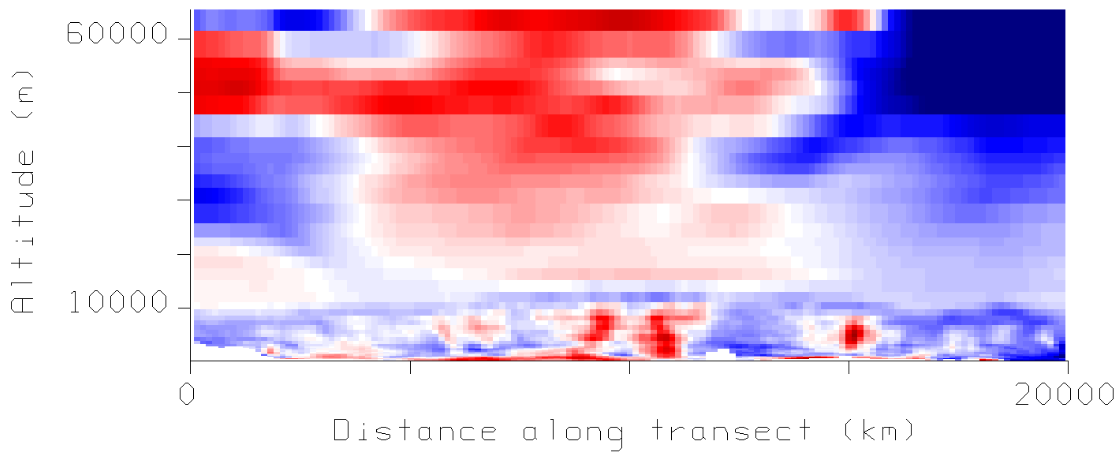
Assignment part 2: Local view

- Make comparison figures between the global average transects and your local cross-sections, and address these questions:
  - Does the moist heating (condensation related processes) correspond to the high cloudiness you infer from the OLR display?
  - Does its vertical gradient imply large PV sources in any places relevant to storm-scale PV budgets?

Diabatic heating

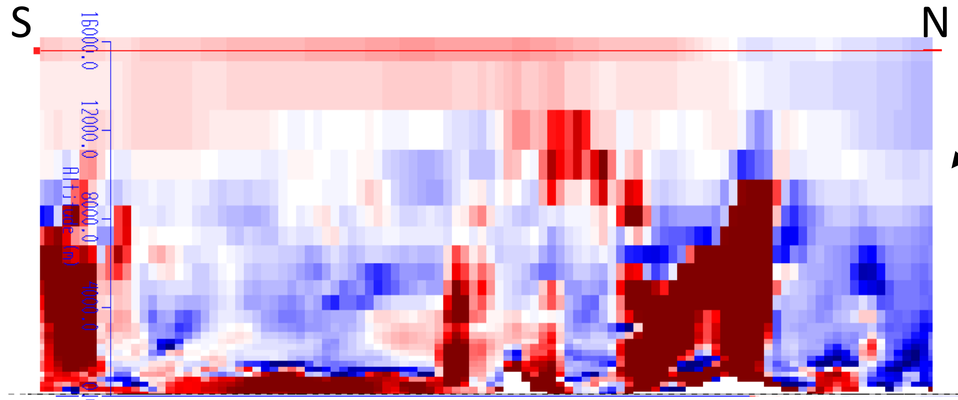
- global average transects

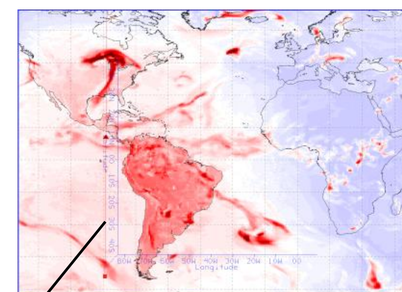
S N



- local cross-sections

S N





Moist heating

- global average transects

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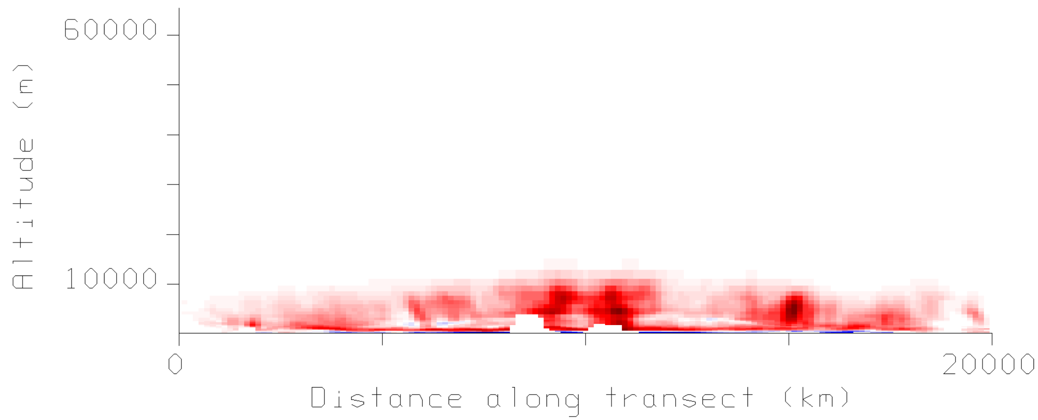
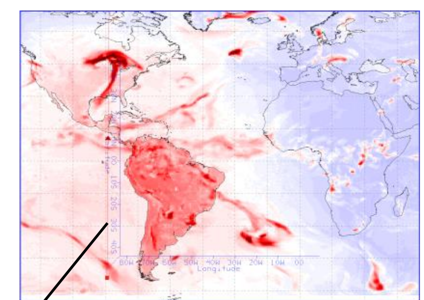
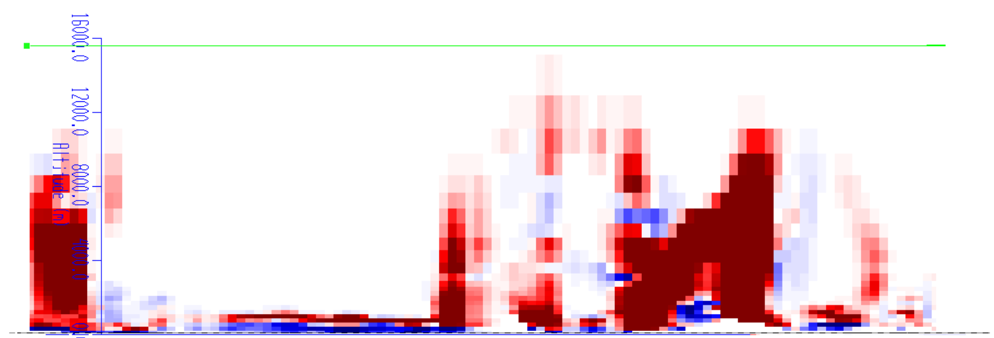




- local cross-sections

S N

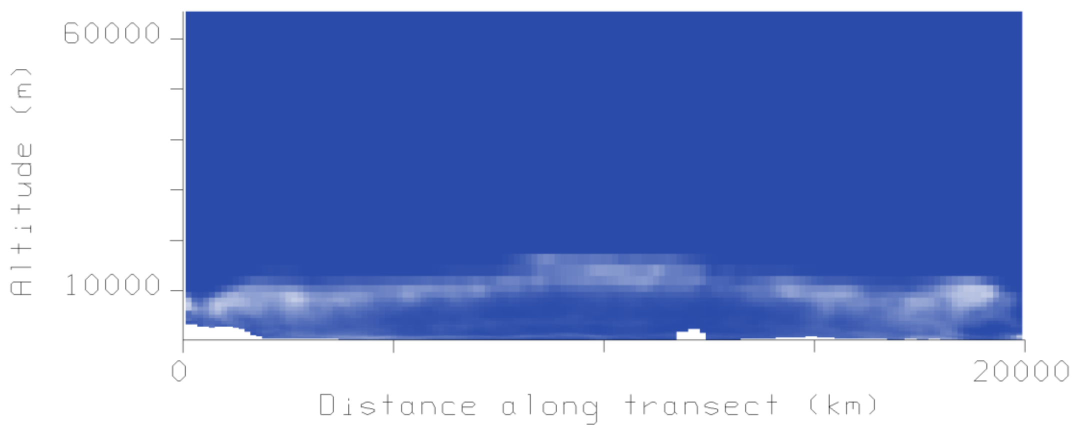


Cloud fraction

High moist heating area is associated with high cloudiness.

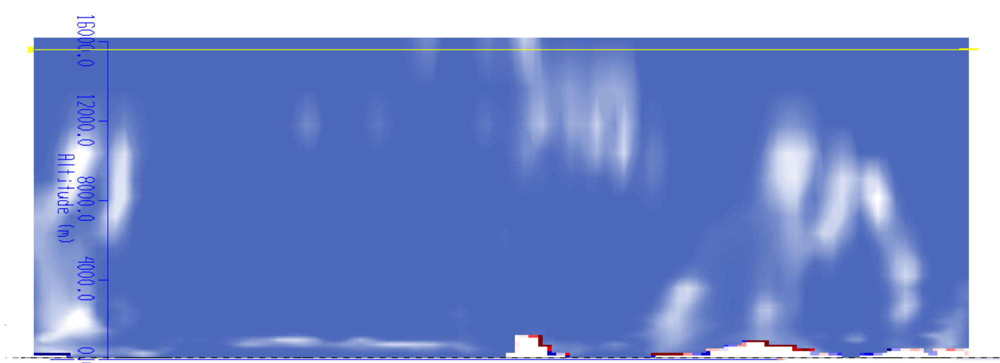
- global average transects

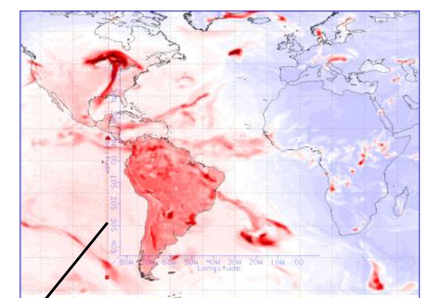
S N



- local cross-sections

S N





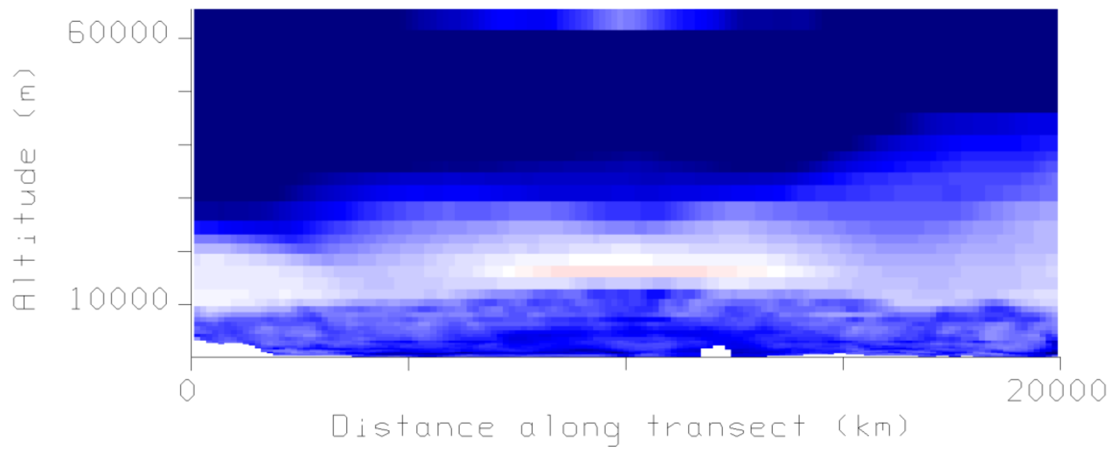
Assignment part 2: Local view

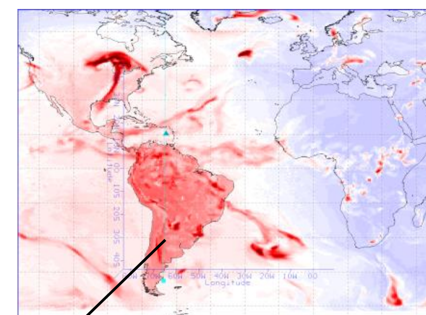
- Make comparison figures between the global average transects and your local cross-sections
  - LW radiation can be understood as water vapor cooling, cloud top cooling, and cloud base warming. Use cloudiness and longwave cross-section images in tandem to show an example of a place where cloud effects are dominant
  - What do these strong vertical heating gradients imply as a PV source?

Longwave heating

- global average transects

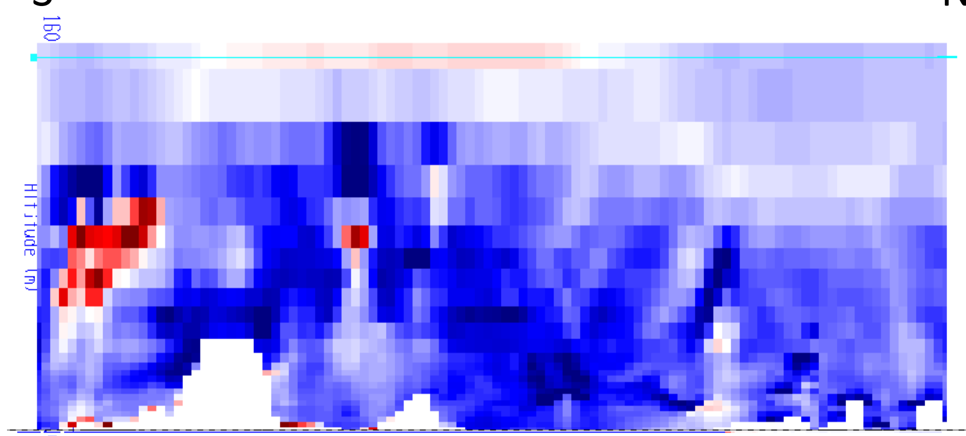
S N





- local cross-sections

S N

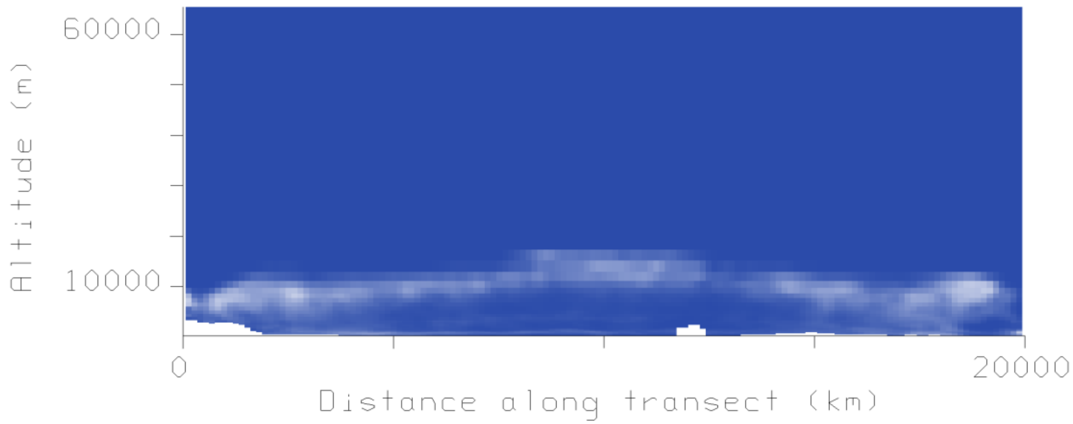


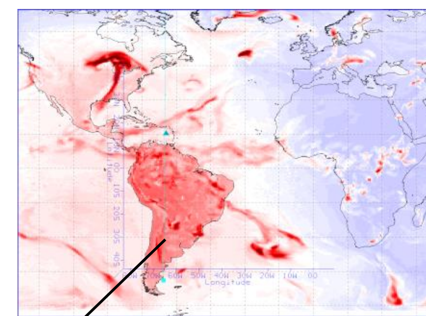
Lon: -65°

Cloud fraction

- global average transects

S N

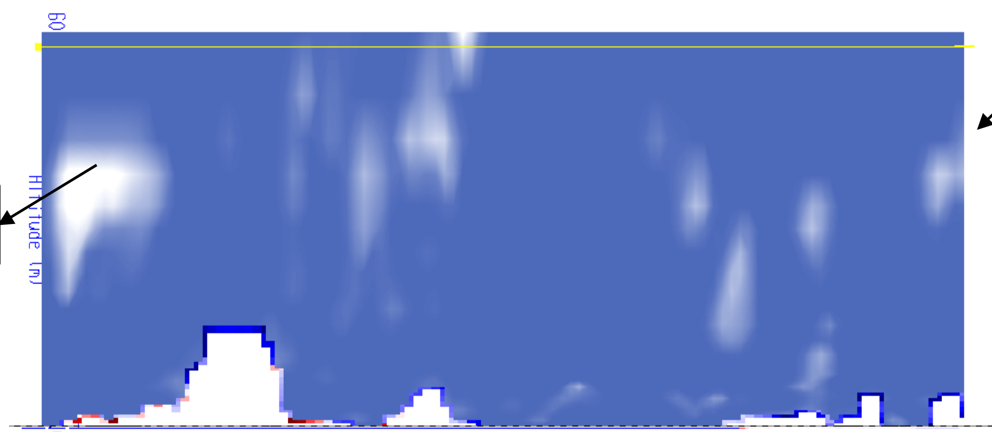




- local cross-sections

S N

cloud effects



"The Primitive Equations" (meaning elemental, fundamental)

$$\frac{D}{Dt}\vec{V}_h = -f\hat{k} \times \vec{V}_h - \vec{\nabla}_p \Phi + \vec{F}_r$$

F=MA in the HORIZONTAL

$$\frac{\partial \Phi}{\partial p} = -\frac{RT}{p}$$

HYDROSTATIC
(w/ ideal gas law to eliminate ρ)

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial \omega}{\partial p} = 0$$

MASS CONSERVATION

$$\frac{\partial T}{\partial t} = -\vec{V} \cdot \vec{\nabla}_p T - \omega S_p + \frac{J}{C_p}$$

FIRST LAW OF THERMO

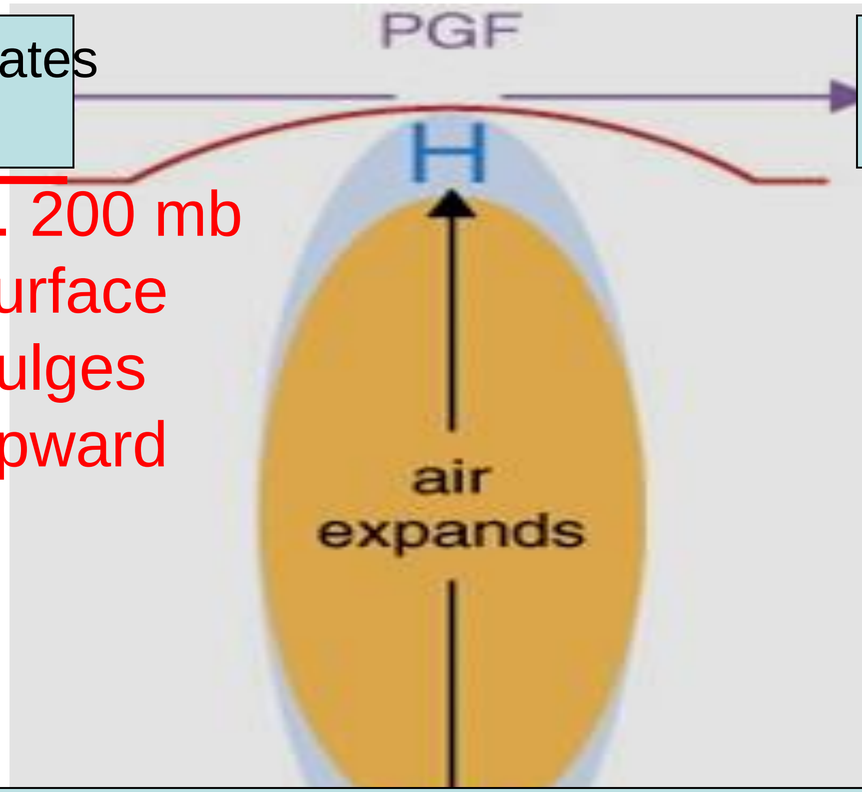
How heated air rises and a warm core vortex develops: the Primitive Equation view. 7 logical steps

1. Warmed column of air gets **thicker**

2. Air accelerates due to PGF

2. Air accelerates due to PGF

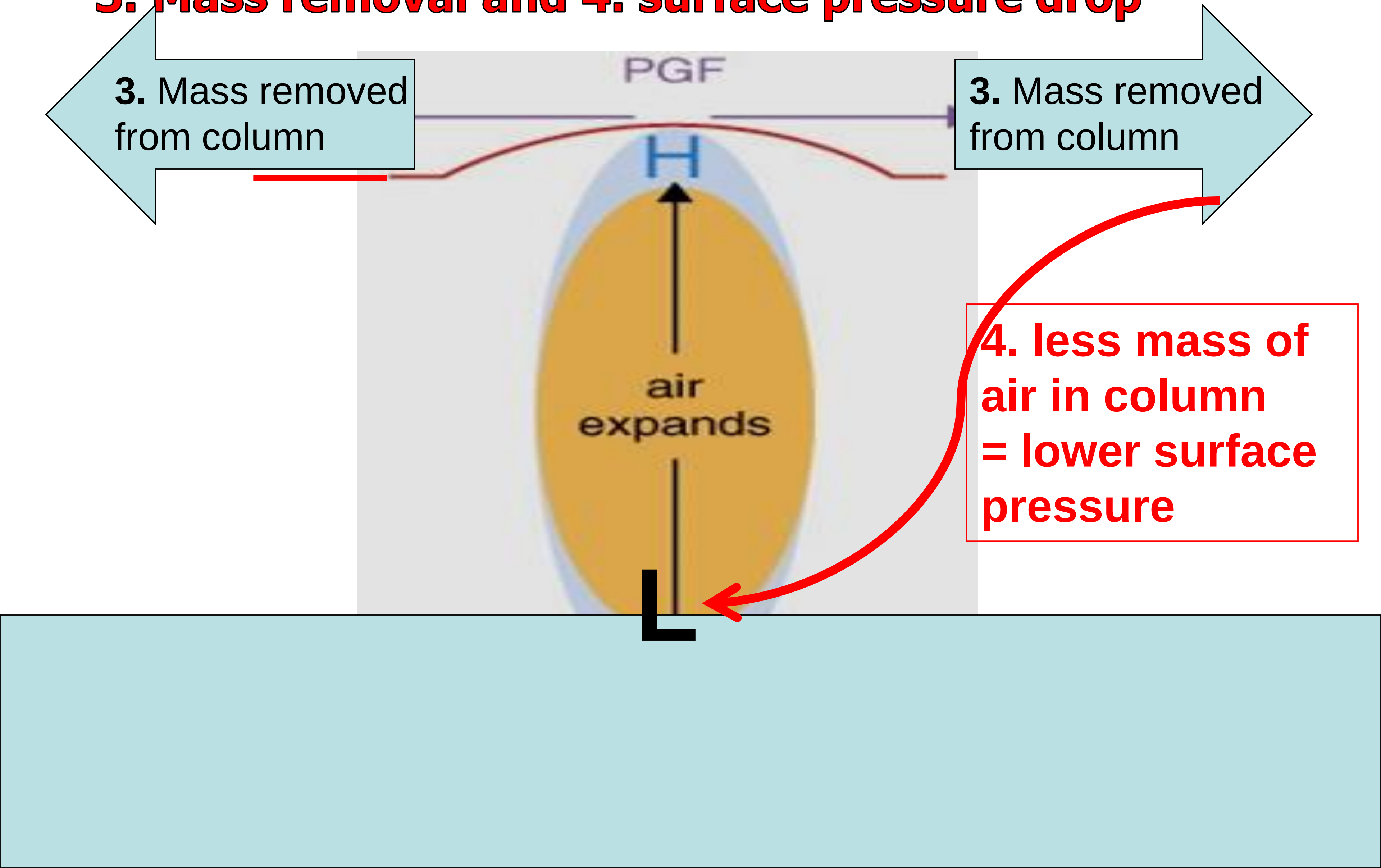
1. 200 mb surface bulges upward



0. Heating (maybe latent heating by condensation in a patch of convection over warm water someplace)

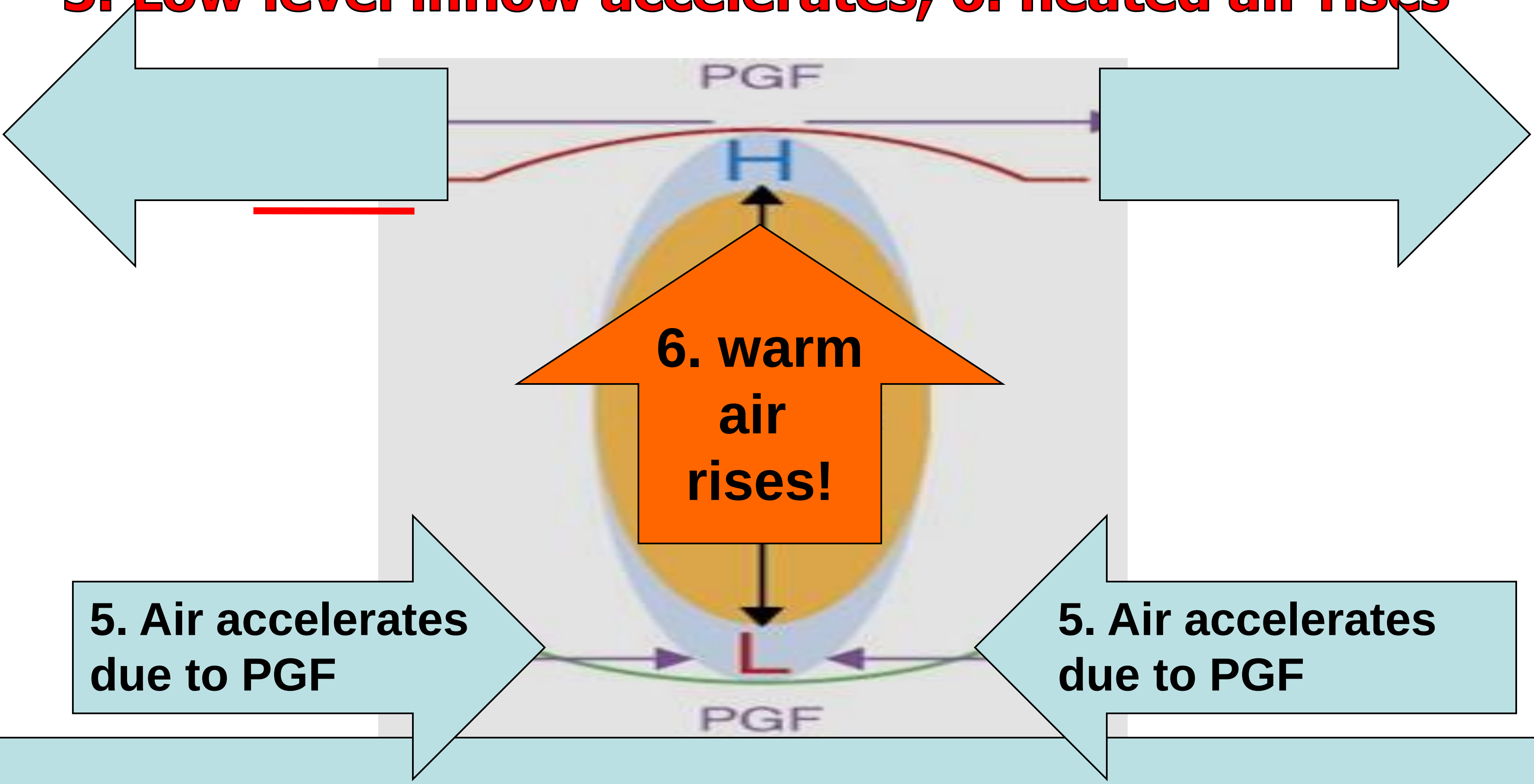
How heated air rises and a warm core vortex develops: the Primitive Equation view. 7 logical steps

3. Mass removal and 4. surface pressure drop

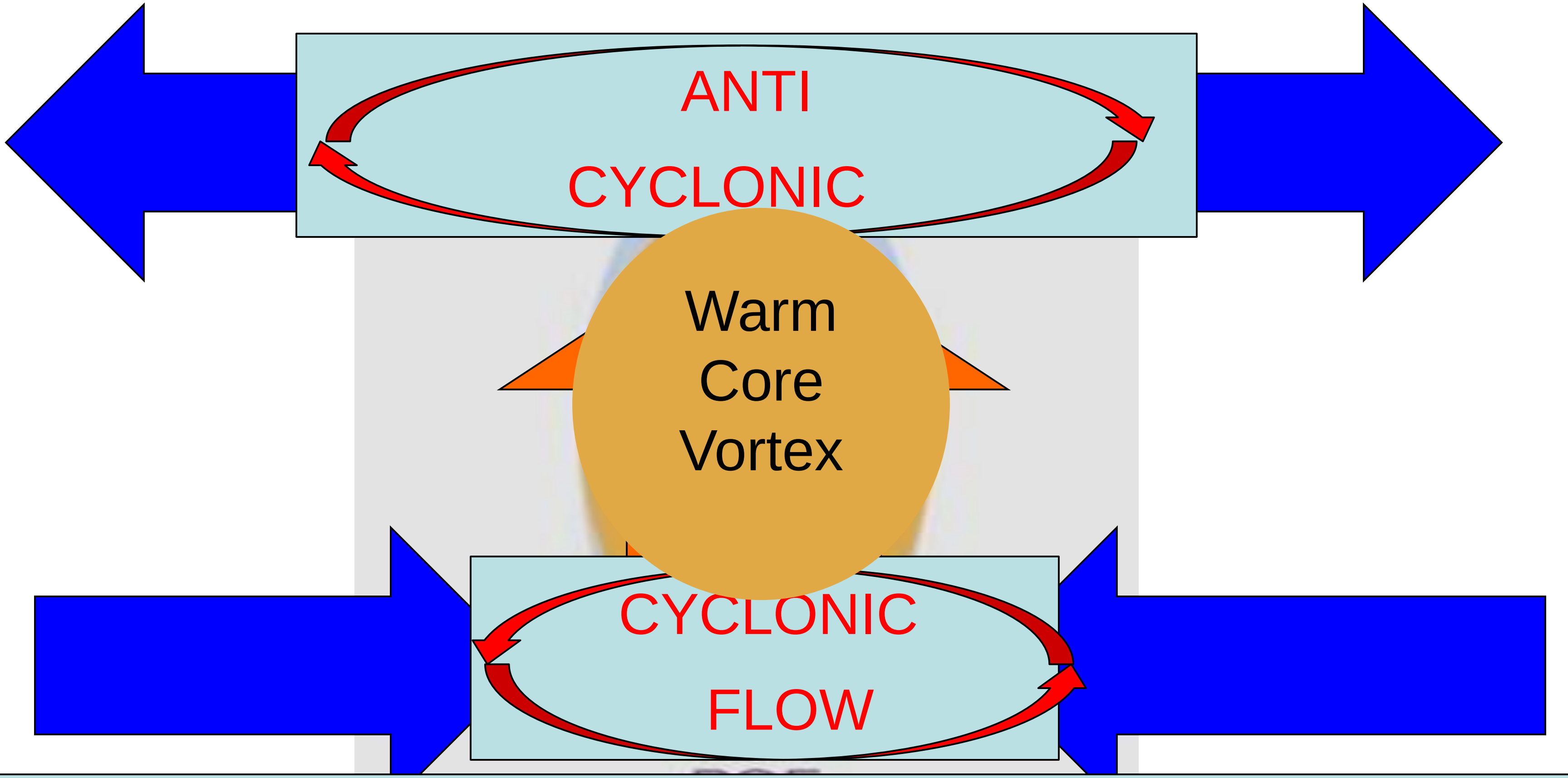


How heated air rises and a warm core vortex develops: the Primitive Equation view. 7 logical steps

5. Low level inflow accelerates, 6. heated air rises



How heated air rises and a warm core vortex develops: the Primitive Equation view. 7 logical steps



7. Coriolis turns flow to right

HW: use The Primitive Equations to compute how a local heating J drives flow in an initially motionless atmosphere

$$\frac{D_h T}{Dt} \boxed{\qquad\qquad} = J/C_p$$

1. J causes T to increase

net change of T =
amount of heat added/Cp

$$\frac{\partial \Phi}{\partial p} = -\frac{RT}{p}$$

2. Warmer **T causes increased thickness** of the heated column

$$\frac{D}{Dt}\vec{V}_h = \boxed{\qquad\qquad\qquad} - \vec{\nabla}_p \Phi$$

3. High Φ over hot column pushes wind outward

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial \omega}{\partial p} = 0$$

4. Surface pressure drops

(remember, omega = Dp/Dt; Holton eq. 3.44)

HW: use The Primitive Equations to compute how a local heating J drives flow in an initially motionless atmosphere

$$\frac{D}{Dt}\vec{V}_h = - \boxed{} - \vec{\nabla}_p \Phi$$

5. Low Φ under hot column pulls wind inward

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial \omega}{\partial p} = 0$$

6. Hot air rises (finally!)

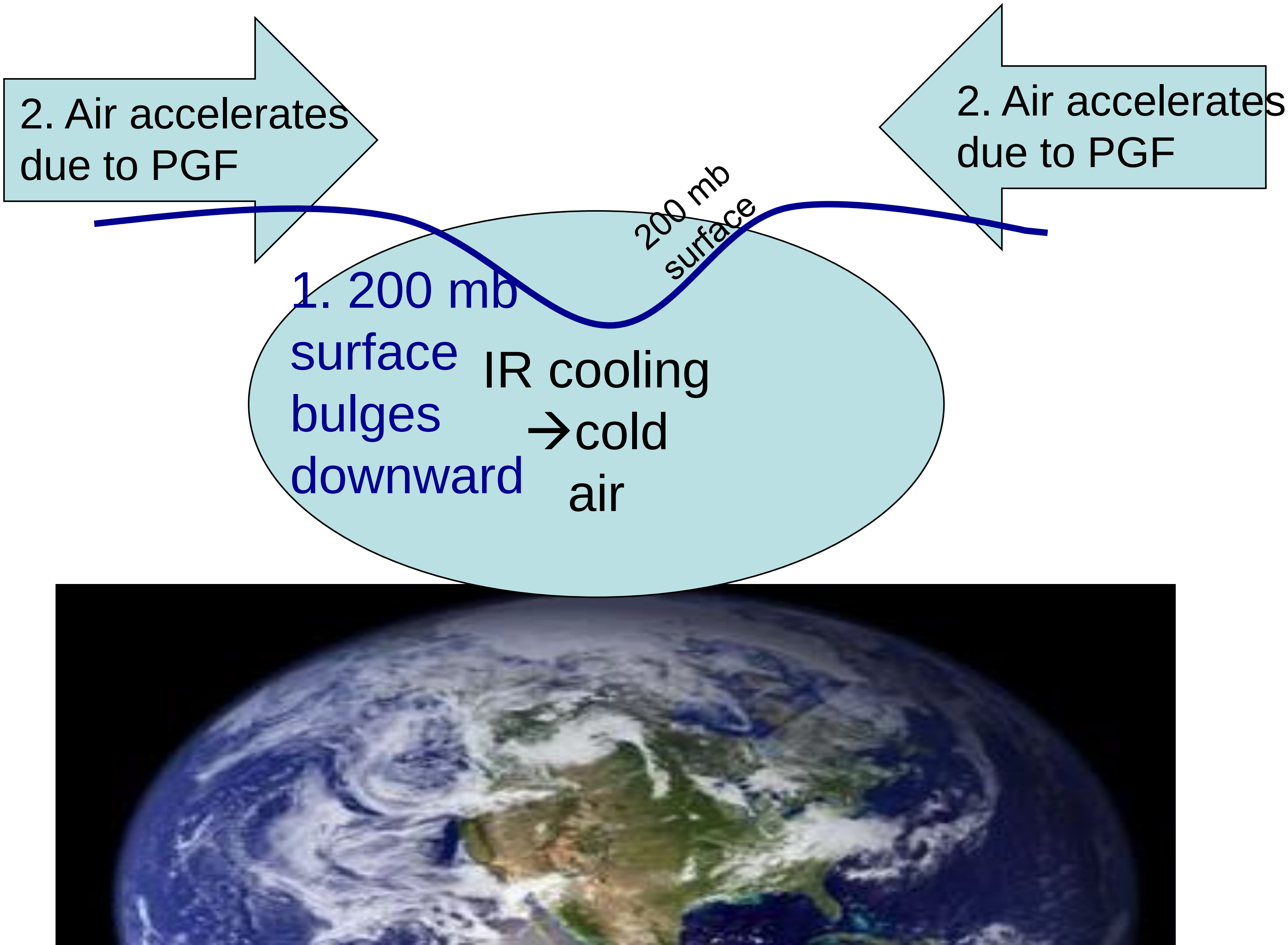
$\omega =\sim \ \rho g w$

$$\frac{D}{Dt}\vec{V}_h = -f\hat{k} \times \vec{V}_h \ \boxed{}$$

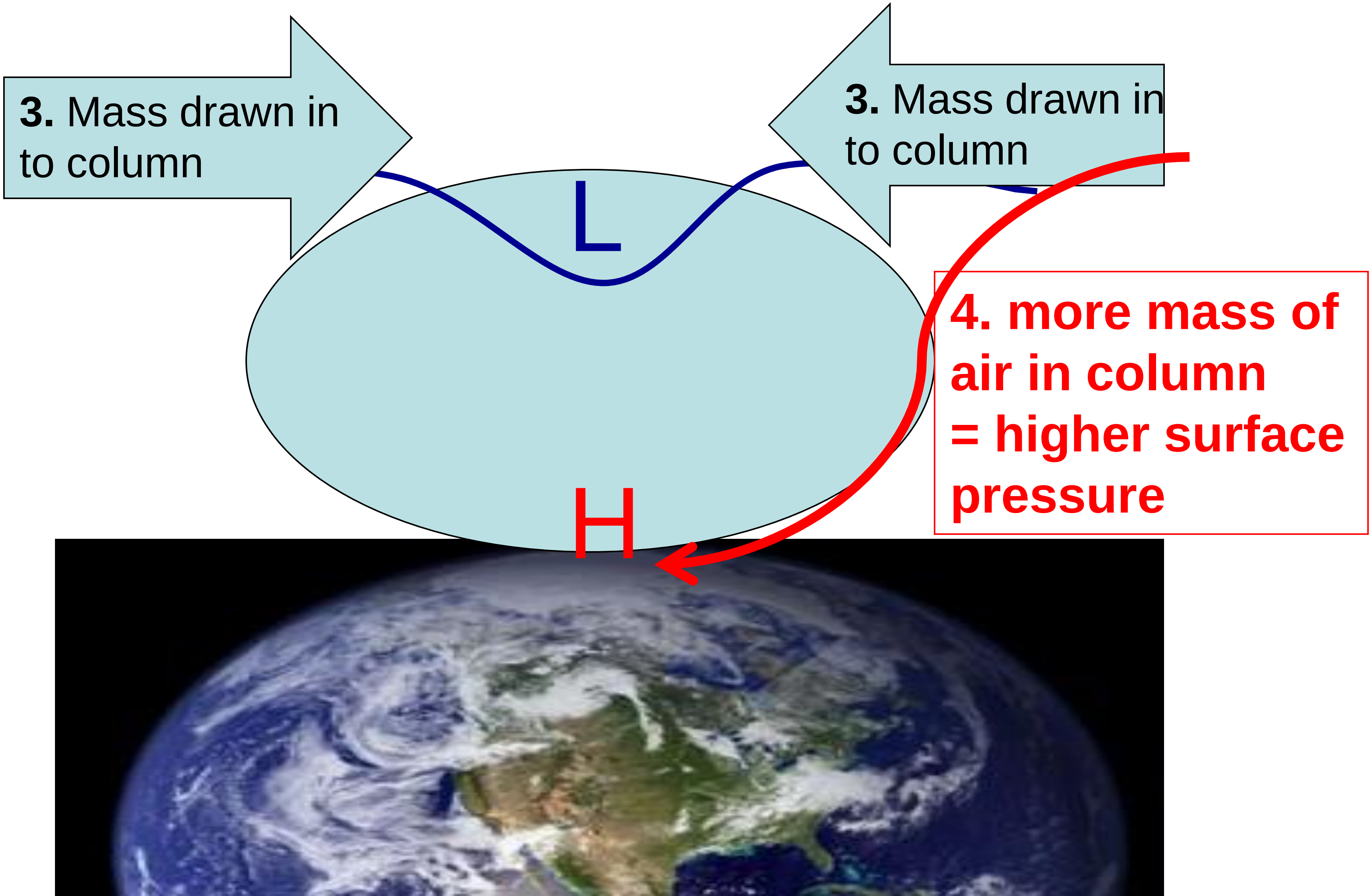
7. Coriolis force turns inflowing and outflowing air to make round-and-round flow

How cooled air sinks and a cool core vortex develops: the Primitive Equation view. 7 logical steps

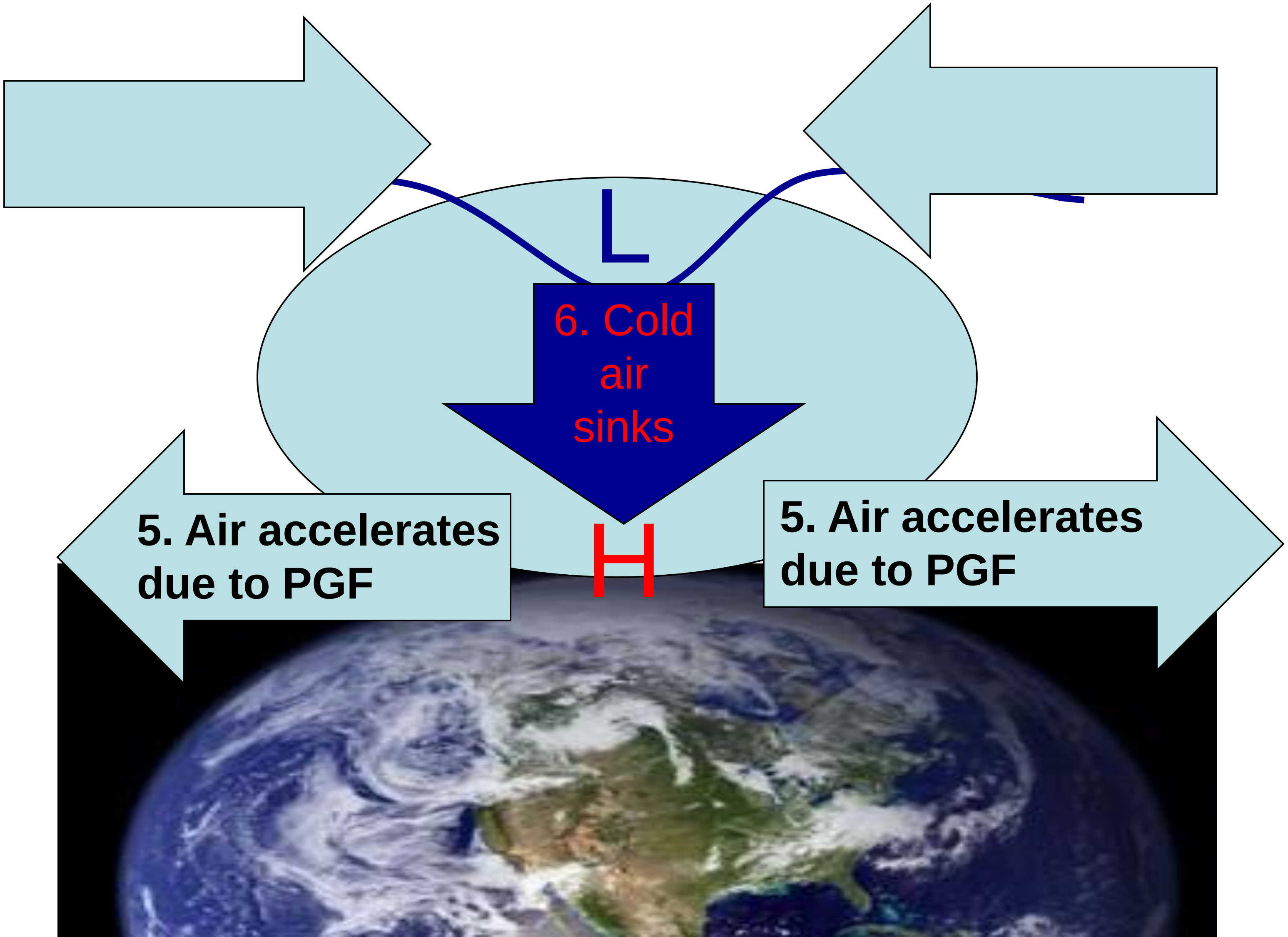
1. Cooled column of air gets **thinner**



How cooled air sinks and a cool core vortex develops: the Primitive Equation view. 7 logical steps

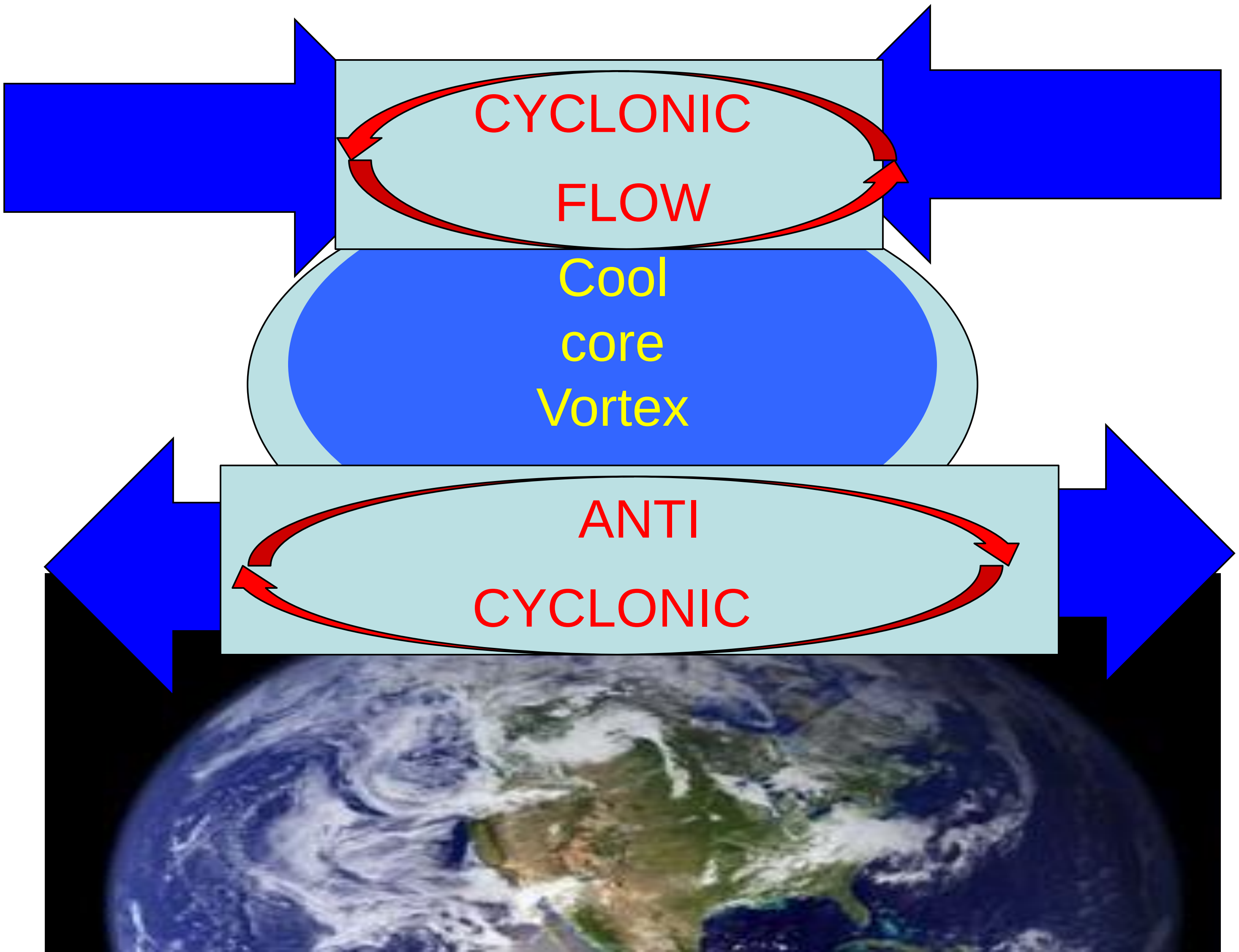


How cooled air sinks and a cool core vortex develops: the Primitive Equation view. 7 logical steps

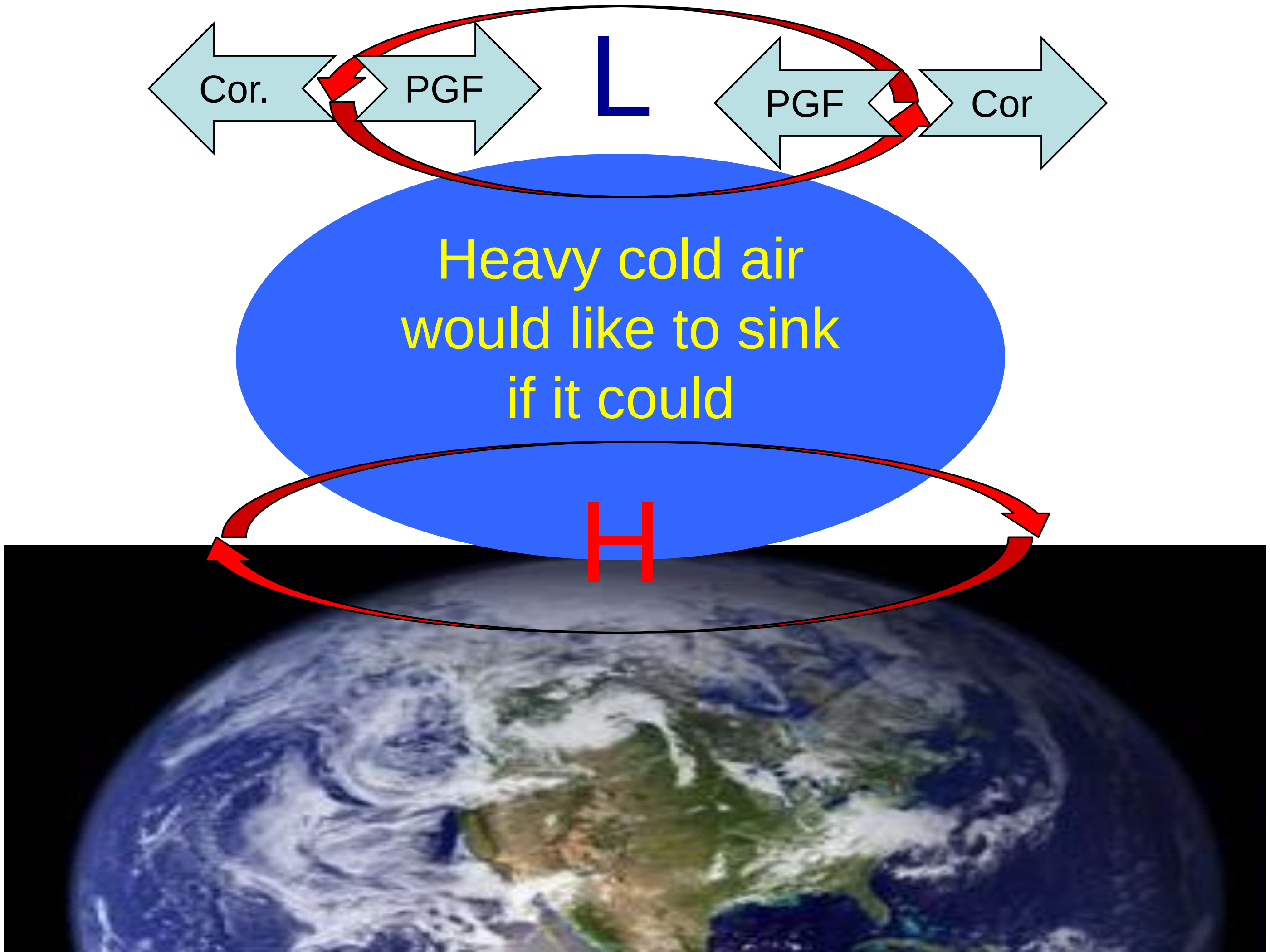


How cooled air sinks and a cool core vortex develops:

7. Coriolis force turns the winds



The geostrophically balanced polar vortex: The Coriolis force on the westerly jet stream prevents cold pool of Arctic air from sinking down and covering the whole Northern Hemisphere



Polar and stratospheric "Reservoirs" of ζ_a or PV

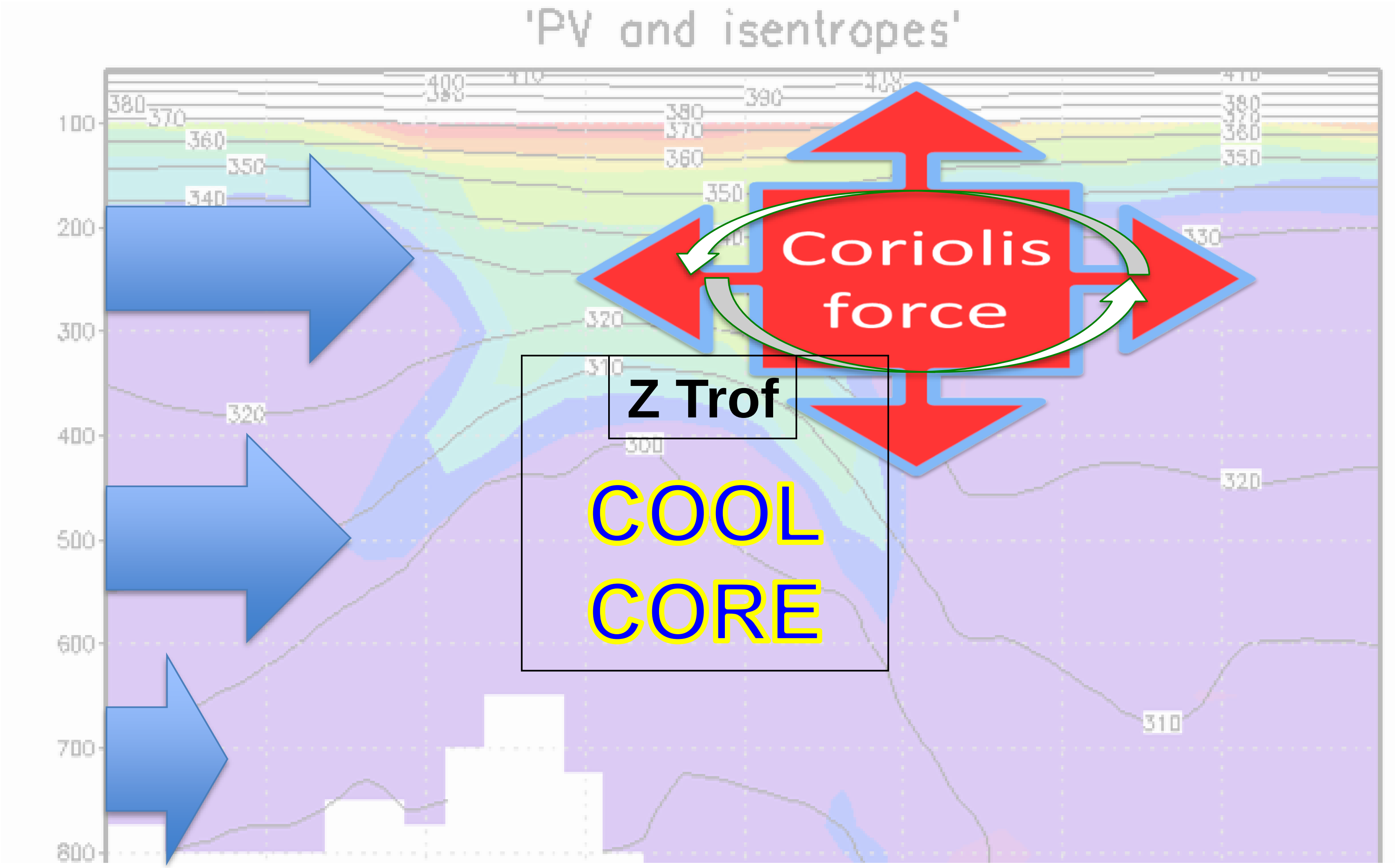
- Potential vorticity: **PV = -g ζ_a ($\partial\theta/\partial p$)**

  - The polar latitudes, where f is large, are a "reservoir" of high PV even when there is no wind!

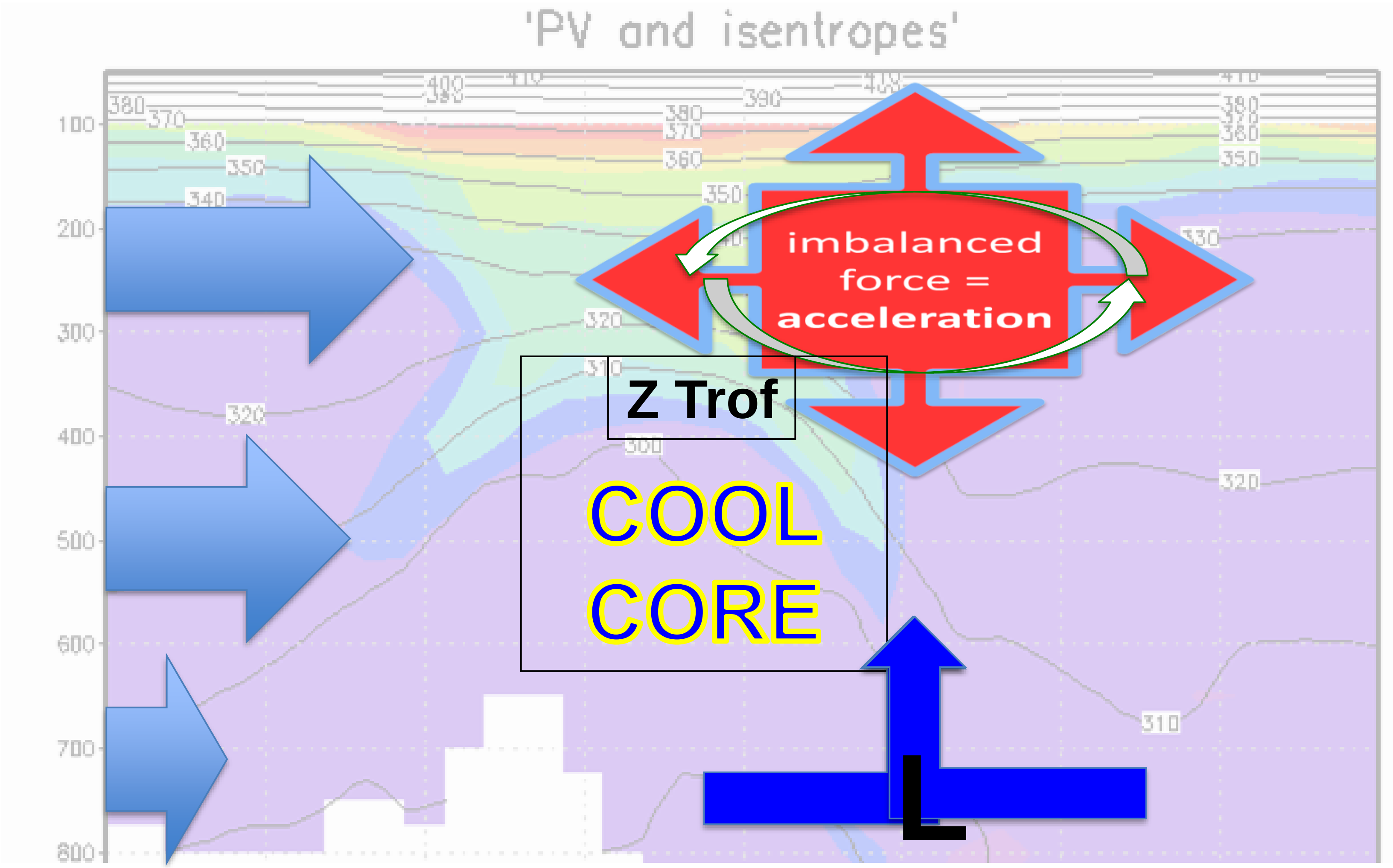
  - The stratosphere where ($\partial\theta/\partial p$) is large is a "reservoir" of PV even when there is no wind!

  - When tentacles or pieces of the polar & stratospheric **PIZZA or OCTOPUS of PV** stretch or break off into the midlatitudes, they become our upper-tropospheric synoptic cyclones.

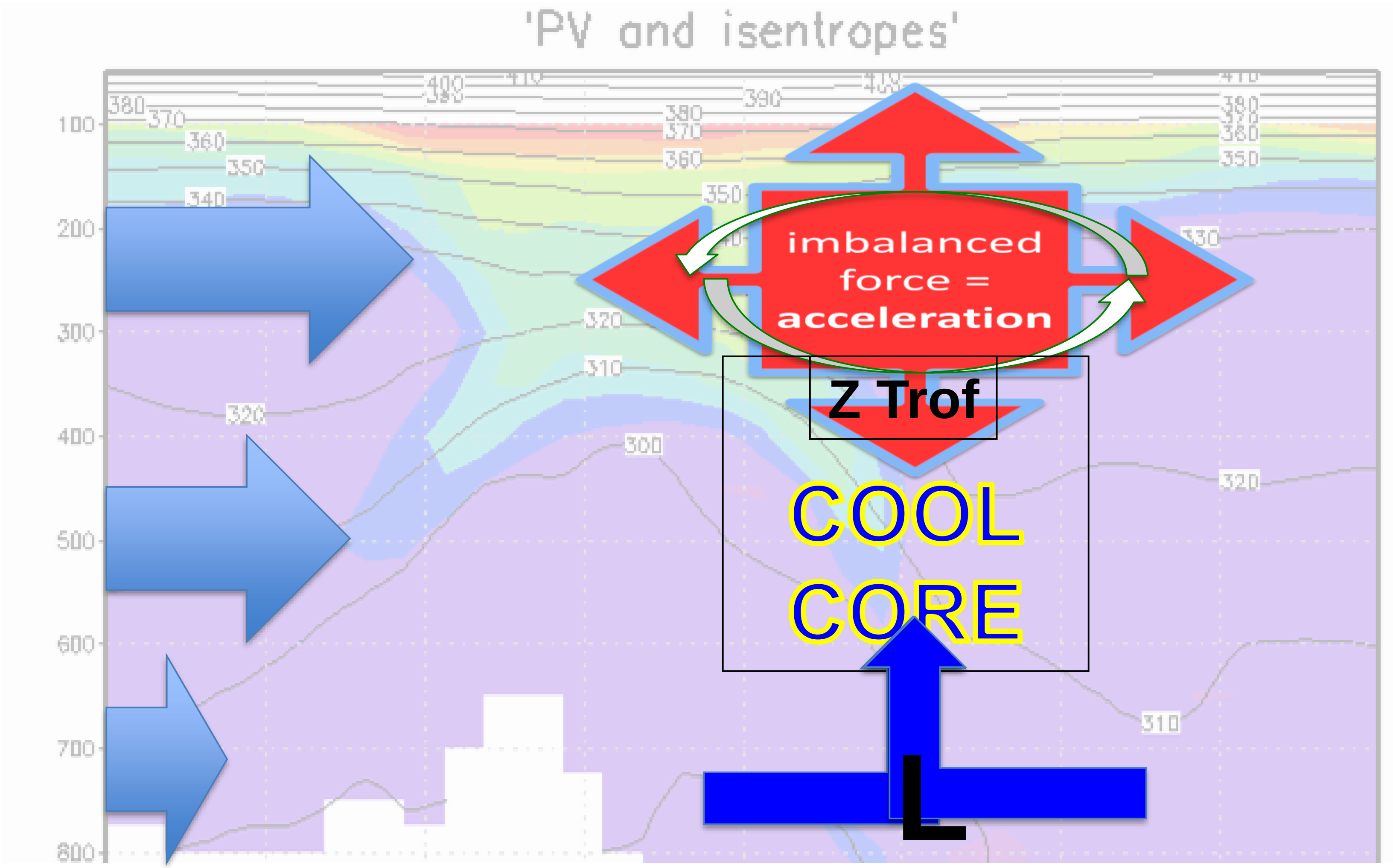
Sheared advection breaks thermal wind balance



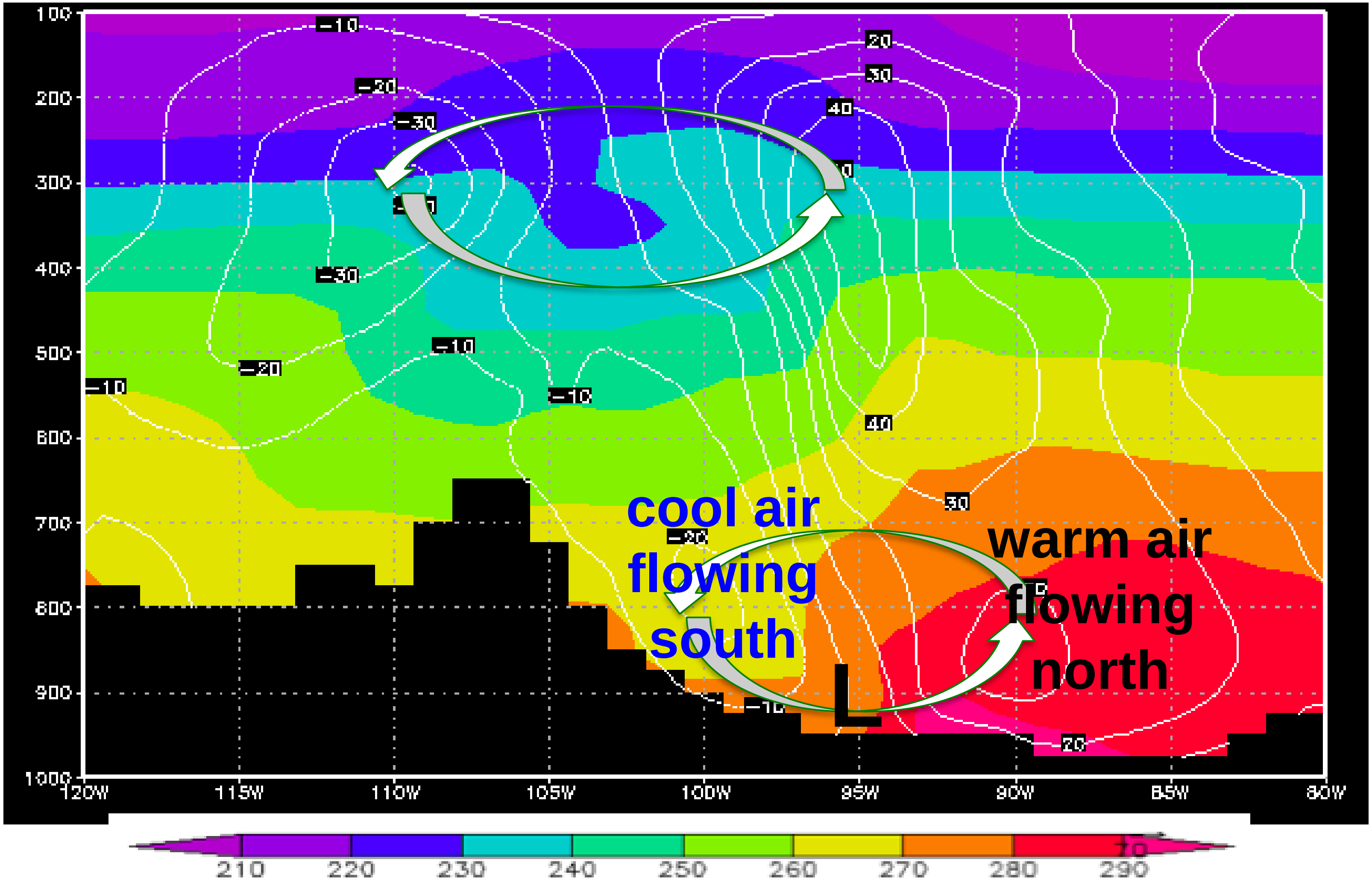
Sheared advection breaks thermal wind balance



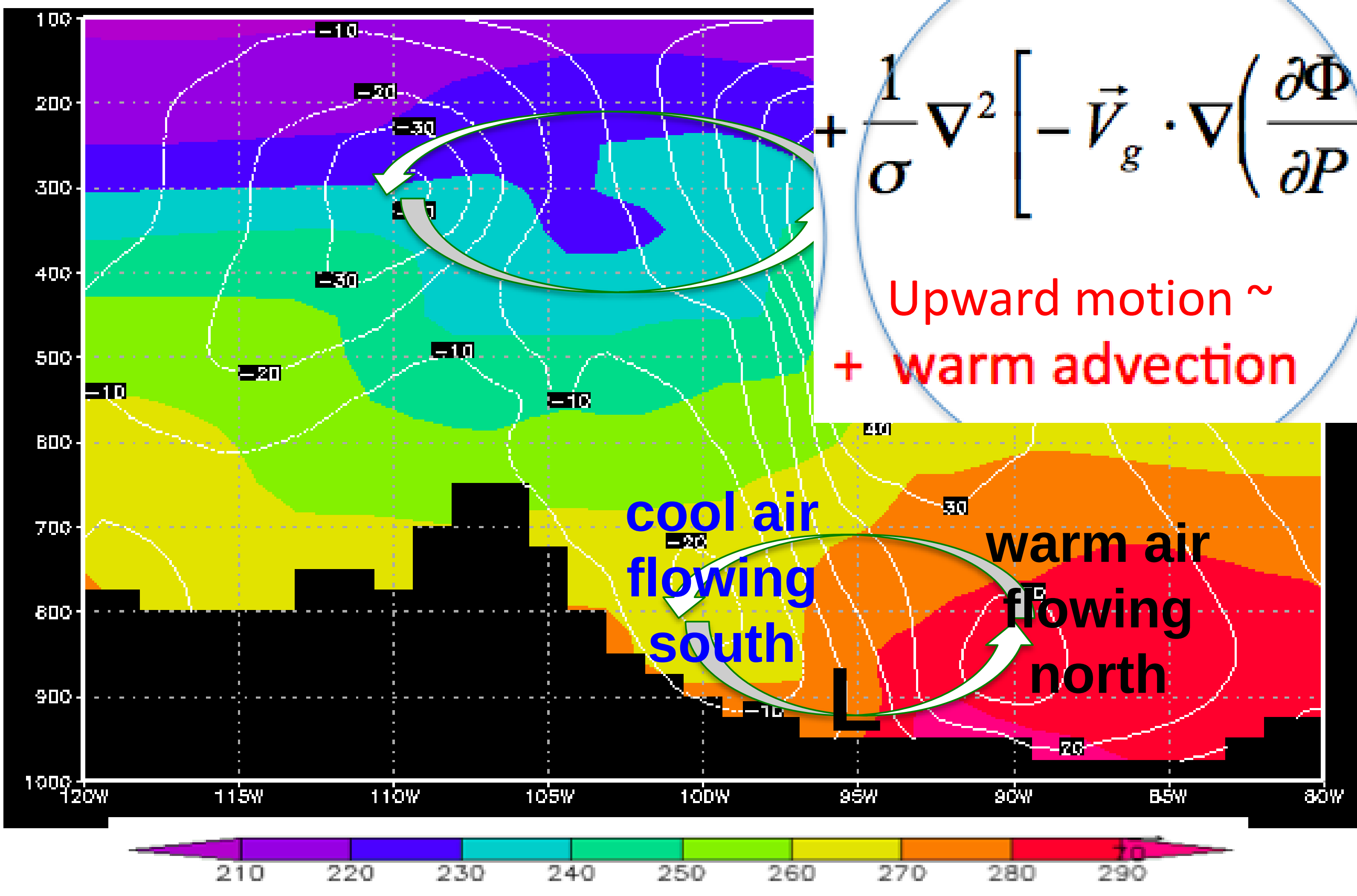
Sheared advection breaks thermal wind balance



But there is some T advection too



But there is some T advection too

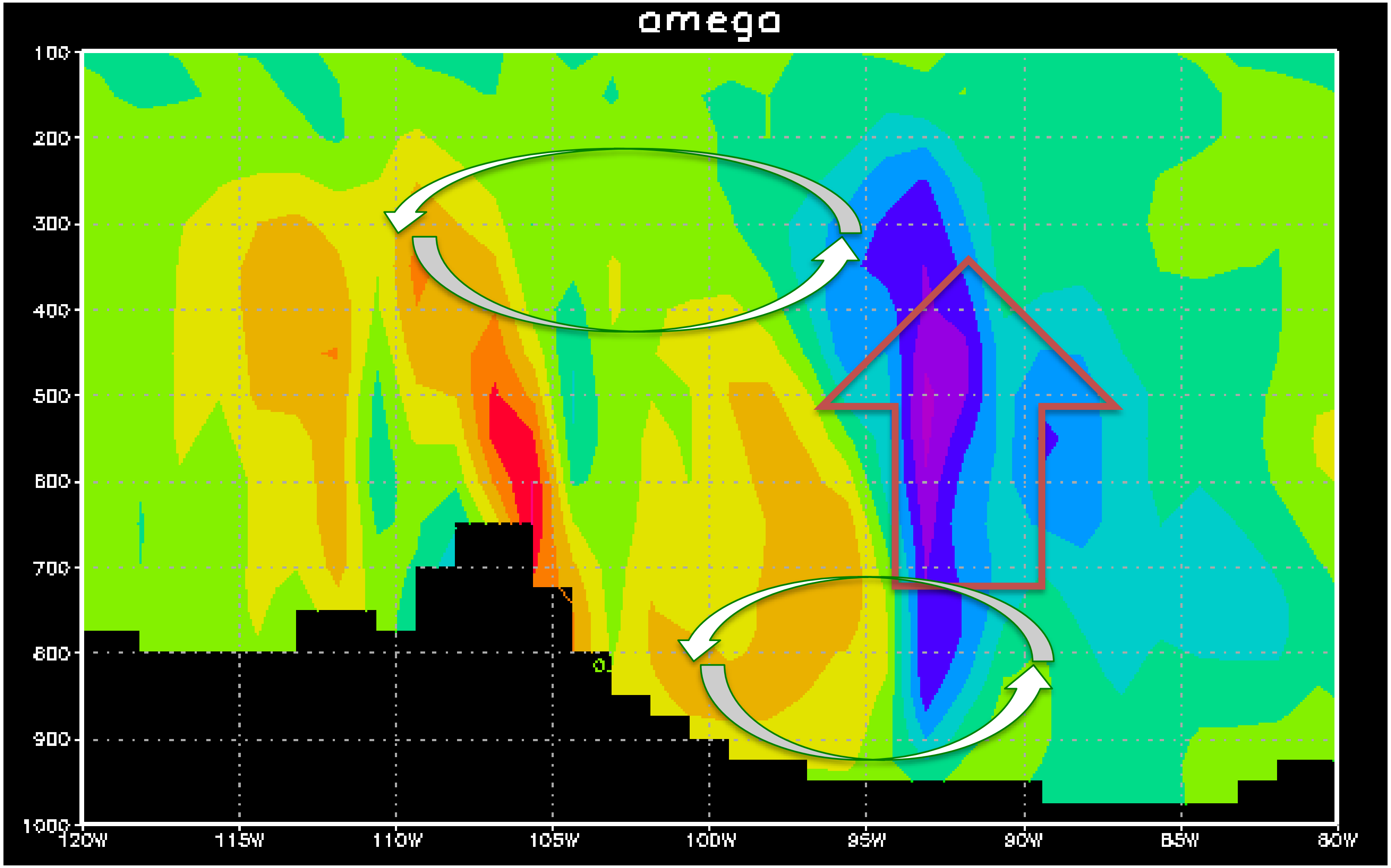


$$+\frac{1}{\sigma}\nabla^2\left[-\vec{V}_g\cdot\nabla\left(\frac{\partial\Phi}{\partial P}\right)\right]$$

Upward motion ~

\+ warm advection

East-west section: omega



Unsheared advection of T, u, v, vort, PV: no breaking of balance